SANITATION CHOICE INVOLVING STAKEHOLDERS

A PARTICIPATORY MULTI-CRITERIA METHOD FOR DRAINAGE AND SANITATION SYSTEM SELECTION IN DEVELOPING CITIES APPLIED IN HO CHI MINH CITY, VIETNAM

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When the sweepers change their profession, they will no longer remain Untouchables. And they can do that soon, for the first thing we will do when we accept the machine will be to introduce the machine which clears dung without anyone having to handle it – the flush system. Then the sweepers can be free from the stigma of untouchability and assume the dignity of status that is their right as useful members of a casteless and classless society.

Untouchable, Mulk Raj Anand (1970) (first published in 1935).

For one person, the typical five-gallon flush contaminates each year about 13,000 gallons of fresh water to move a mere 165 gallons of body waste. What this means is that we're taking a valuable, clean resource – water – and a potentially valuable resource – human excrement – and mixing them together to pollute the water and make the fertilizer potential of body wastes just about useless.

Goodbye to the Flush Toilet (Hupping Stoner, 1977).

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LIST OF ABBREVIATIONS AND SYMBOLS

Technology-related abbreviations

AAD	Accumulating Anaerobic Digester
AD	Anaerobic Digestion (or Digester)
AGR	Attached-Growth Reactor
AT	Aeration Tank
AF	Anaerobic Filter
AS	Activated Sludge (Treatment)
AS+F	Activated Sludge plus Filter
ASTR	Anaerobic (Completely) Stirred Tank Reactor
AUF	Anaerobic Upflow Filtration (or Filter)
BAST	Baffled Anaerobic Septic Tank
BASTAF	Baffled Anaerobic Septic Tank with Anaerobic Filter
BOD_5	Biological Oxygen Demand (5 days test at 20^{o} C)
CF	Cistern Flush (toilet)
CHP	Combined Heat and Power
CMAS	Completely Mixed Activated Sludge
COD	Chemical Oxygen Demand
CS	Combined Sewer
CSO	Combined Sewer Overflow
CSTR	Completely Stirred Tank Reactor
DC	Direct Construction Costs
DESAR	Decentralized Sanitation and Reuse
DEW	Dewatering
DEWATS	Decentralized Wastewater Treatment Systems
DHS	Downflow Hanging Sponge
DWF	Dry-Weather Flow
DWS	Drinking-Water Supply
EA	Extended Aeration
FC	Faecal Coliform
HC	House Connection
HE	Helminth Eggs
HFCW	Horizontal-Flow Constructed Wetland
HFST	Horizontal-Flow Septic Tank
HFSTAF	Horizontal-Flow Septic Tank with Anaerobic Filter
HFPF	Horizontal-Flow Planted Filter
HFRB	Horizontal-Flow Reed Bed filter
hh	Household
HIC	High-income Countries
HRT	Hydraulic Retention Time
HTH	High Test Hypochlorite (Calcium hypochlorite)
Inh	Inhabitant
JM	Junction Manhole
LIC	Low-Income Countries
MAP	MagnesiumAmmoniumPhosphate

MBR	Membrane Bioreactor
MBBR	Mobile or Moving Bed Reactor
MLSS	Mixed Liquor Suspended Solids
MSL	Mean Sea Level
OD	Oxydation Ditch
PE	Population Equivalent
PF	Pour-Flush (toilet)
RBC	Rotating Biological Contactor
SAF	Submerged Aerated (bio)Filter
SB-AS	Sequencing Batch Activated Sludge
SFCW	Surface-Flow Constructed Wetland
SRT	Sludge Retention Time
SS	Suspended Solids
SSF	SubSurface Flow
SSO	StormSewer Overflow
ST	Septic Tank
STOD	Stormwater-Overflow Device
STW	Sewage-Treatment Works
TC	Total Coliforms
TCVN	Vietnamese Standard
TF	Trickling Filter
TH	Thickener
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Bed reactor
UASB-ST	UASB Septic Tank
UD	Urine-Diverting (toilet)
VACB	Garden-pond-pig-biogas integrated farming system
VFCW	Vertical-Flow Constructed Wetland
VFPF	Vertical-Flow Planted Filter
VFRB	Vertical-Flow Reed Bed filter
V(S)S	Volatile (Suspended) Solids
WSP	Waste Stabilization Pond(s)
WW	Wastewater
WWT	Wastewater Treatment
WWTP	Wastewater-Treatment Plant

Institutional abbreviations

ADB	Asian Development Bank
BTC	Belgian Technical Cooperation
CDM	Camp Dresser & McKee International Inc.
CENTEMA	Center for Environmental Technology and Management
CEFINEA	Centre for Water and Environmental Research
DARD	Department of Agriculture and Rural Development
DE	Drainage Enterprise
DLH	Department of Land and Housing
DOC	Department of Construction
DOF	Department of Finance
DOH	Department of Health
DONRE	Department of Natural Resources and Environment
DPA	Department of Urban Planning and Architecture
DPI	Department of Planning and Investment
DT	Department of Transportation
DPWC	District Public Works Companies
DTPW	Department of Transportation and Public Works
EU	European Union
GTZ	(Deutsche) Gesellschaft für Technische Zusammenarbeit
HCMC	Ho Chi Minh City
HUUP	Ho Chi Minh City Urban Upgrading Project
JIBC	Japan Bank of International Cooperation
JICA	Japan International Cooperation Agency
JSC	Joint-Stock Company
MARD	Ministry of Agriculture and Rural Development
MOC	Ministry of Construction
MOH	Ministry of Health
MONRE	Ministry of Natural Resources and Environment
MOTC	Ministry of Transport and Communications
MUT	Management of Urban Transport
ODA	Official Development Assistance
PC-HCMC	People’s Committee of Ho Chi Minh City
PCI	Pacific Consultants International
PMU	Project Management Unit
ROPETIZ	Relocation of Polluting Enterprises to Industrial Zones
SAWACO	Saigon Water Company
SANCHIS	Sanitation Choice Involving Stakeholders
THLG	Tan-Hoa Lo-Gom sanitation and urban upgrading project
UDC	Urban Drainage Company
UMD	Urban Management Division
UPI	Urban Planning Institute
UPWC	Urban Public Works Company
UTMD	Urban Transport Management Department

VITTEP	Vietnamese Institute for Tropical Technology and Environmental Protection
VUUP	Vietnam Urban Upgrading Project
WB	World Bank
WHO	World Health Organization
WSSCC	Water Supply and Sanitation Collaborative Council

Costs and finance-related symbols

AC	Annual capital costs (USD/yr)
B_r	Annual recurrent benefits (USD/yr)
B_{rH}	Annual recurrent benefits per household (USD/hh.yr)
C_c	Construction costs of a project (USD)
C_{cH}	Construction costs of a project per household (USD/hh)
C_{cHD}	Construction costs per household depending on population density (USD/hh)
C_r	Annual recurrent costs (O&M) of a project (USD/yr)
C_{rH}	Annual recurrent costs (O&M) per household (USD/hh.yr)
C_{Tr}	Treatment costs of wastewater (USD/m^3)
CRF	Cost recovery factor(yr^{-1})
i	Minimum attractive rate of return (MARR) (percentage * 0.01*yr^{-1})
N	Number of households serviced
R	Relative cost factor of system as compared to reference system (dimensionless)
t	Time (yr)
T	Design life time (yr)
TABH	Total annual benefits per household (USD/hh.yr)
TAC	Total annual costs of project (USD/yr)
TACH	Total annual costs per household (USD/hh.yr)
USD	United States Dollar

CHAPTER 1 INTRODUCTION

1.1 The challenges of environmental infrastructure in developing countries

The management of water, sanitation and solid-waste in developing countries faces two main challenges:

- the provisions insufficiently reach the poor,
- the increasing consumption of water, food, energy and other natural resources leads to alarming resources constraints and unacceptable environmental pollution.

The efforts to address these two problem complexes are often referred to by the Brown respectively the Green Agenda in urban environmental management (McGranahan et al., 2001, p 5, p 170). The Brown agenda aims at giving all people access to safe drinking water and basic sanitation and has been concretized in the Millennium Development Goals, Goal 7, targets 3 and 4 (UNDP, 2010). In the words of the Millennium Development Goals the Green Agenda stands for the integration of sustainable-development principles into country policies and programmes and reversal of the loss of environmental resources in order to avert the anticipated collapse of global and regional ecosystems and societies (MDG Goal 7, target 1). In the domain of urban sanitation this target demands a drastic reduction of the emissions of polluting substances to the environment and a change from consumption to recovery of resources. One of the important principles is the closing of material cycles (O'Rourke et al., 1996).

During the past decades city administrations in developing countries and their public services have worked hard to modernize their water and sanitation infrastructure. These efforts take place against the backdrop of a stormy urban growth, in general not matched by the development of adequate governance, strongly limited means and a far from homogeneous urban structure. Cities consist of planned and unplanned areas with a strongly different social and economic characteristics, infrastructure, and opportunities for future welfare. Under these conditions time and again adequate provision of basic services to all has proven to be an elusive target.

Against this background of inadequate provision and the need of radical modernization of environmental infrastructure, new approaches in planning, management of infrastructure and information, and technologies are required that are certainly different from what is known at present. This thesis sets itself the task of reconnoitring innovative approaches and has chosen to do this taking the example of Ho Chi Minh City in Vietnam. The case-study on the one hand delivers a wealth of insight in concrete challenges and opportunities and on the other hand constitutes a space where new ideas can be discussed and tested.

1.2 Drainage and sanitation in Ho Chi Minh City: a case-study

Ho Chi Minh City is the largest city of Vietnam and its economic powerhouse. At present it counts approximately 7 million inhabitants and is generating about 25% of the gross domestic product of the country. For several reasons Ho Chi Minh City is an interesting and utterly relevant case to study the challenges and testing new approaches in urban infrastructure

development. (1) The city is undergoing rapid growth of the population and large new urbanizations have emerged without adequate planning. These unplanned areas in particular are beset with serious infrastructure problems, whose solution is the topic of this study. In the initial stage of the work on this thesis the author found that the 1999 Drainage and Sanitation Master Plan of the city hardly pays attention to the dynamics of housing development and the problems of drainage and sanitation in these unplanned settlements, nor to the challenges associated with the Green Agenda (JICA/ Pacific Consultants International, 1999f).
(2) The city is situated in coastal and riverain low lands and has large parts constructed in flood plains. In the perspective of a rising sea level drainage and sanitation and protection against flooding of built-up areas in these plains is a matter of high priority which has been recognized by the city’s administration recently. The threat of flooding Ho Chi Minh City has much in common with several other large cities in Asia. (3) It is a city with much perspective thanks to its propitious economic situation. In Vietnam, but perhaps even within the South East Asian region, it is a testing ground for new approaches in the domain of environmental technologies and management of urban upgrading and development. The innovations in Ho Chi Minh City may readily spread to other cities in the region (Mol and Van Buuren, 2003, p 7).

The work on this thesis was started with a study about the water management problems of the city and their possible solutions. Important aspects are the growth of the city, its policies in the domains of housing and infrastructure, the physical characteristics and development of infrastructure and the related challenges to urban planning and management. Theories were explored about new approaches to environmental infrastructure planning and management (chapter 2), and attempts were made to elaborate designs of drainage and sanitation hardware for the unplanned neighborhoods. During the work on the latter it turned out to be impossible to propose *generic* satisfactory technical drainage and sanitation solutions for the target areas on the basis of the developed problem analysis. This was among other things due to the strongly diverging physical and social characteristics of these areas, but also to the scant experience with innovative more environment-friendly systems. It was inferred that solutions had to be responsive to local conditions and problems, and be endorsed by the involved communities. Accordingly, the infrastructure development requires a joint decision-making process involving all relevant stakeholders, resulting in technical and management solutions that may differ between areas. The outcome of such a process has been indicated as *mixed modernities* (Spaargaren et al., 2006; Oosterveer and Spaargaren, 2010).

Starting from the apparent need to guide a multi-stakeholder decision-making process in drainage and sanitation system selection, a learning and decision-making method has been developed (chapters 3 –7) based on multi-criteria decision analysis (MCDA) theory. This tool has been named SANCHIS, which means: Sanitation Choice Involving Stakeholders. The new method required testing in practice, while at the same time the practice also needed the method. While this SANCHIS method was elaborated, also the analysis of the drainage and sanitation infrastructure development in Ho Chi Minh City has been continued resulting in the chapters 8 and 9. The use of the method for the screening and assessment of drainage and sanitation systems in different built-up areas in Ho Chi Minh City has been elaborated in chapter 10 and its application as a learning and decision-making method during multi-stakeholder workshops in chapter 11. A discussion of the research findings in this thesis and its contribution to the drainage and sanitation planning practice is presented in the final chapter 12.

The interrelationships between the chapters of this thesis are shown in figure 1.1. This figure can be understood as the conceptual framework of the study. The arrows in the figure indicate the direction of the flow of information and accordingly shows the order in which the various chapters were elaborated. The objectives and research questions of this thesis are formulated in the next section 1.3.

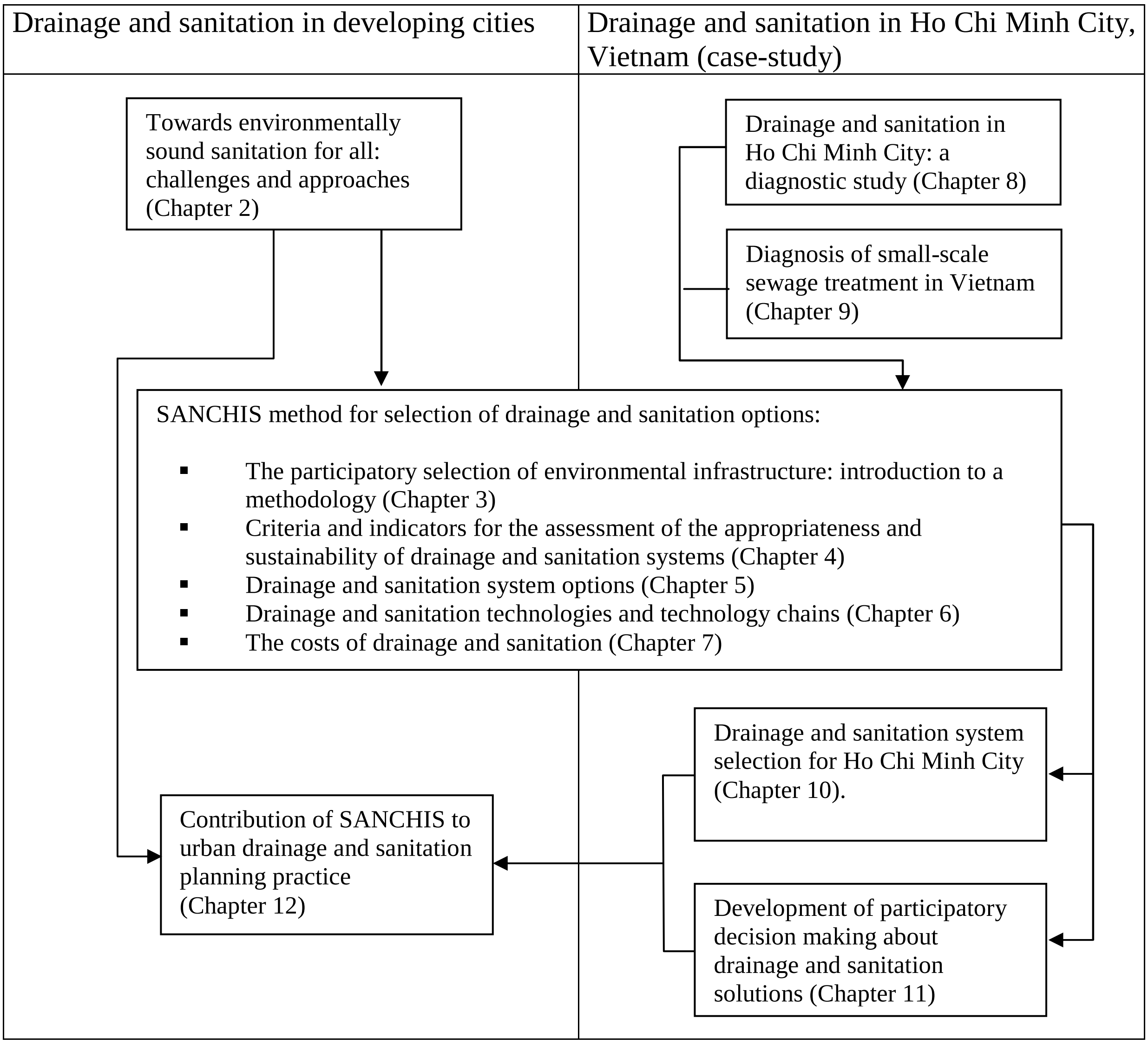

Figure 1.1 Conceptual framework of this thesis.

1.3 Objectives, research questions and methods

1.3.1 Societal and research objective

With the societal objective of having delivered a tangible contribution to a sustainable urban drainage and sanitation planning practice in developing countries, particularly in unplanned urban areas of Vietnam, the research objective of this dissertation is:

- *To have elaborated adequate and accepted drainage and sanitation solutions for unplanned areas in Ho Chi Minh City, Vietnam.*

The emphasis in this thesis is on a community-based drainage and sanitation approach as an alternative to both large-scale centralized sanitation and individual on-site treatment.

The overall research objective is being attained by finding the answers to the research questions listed below in subsection 1.3.2. This subsection posits these research questions as the backbones of the chapters in this thesis. The content of each chapter and the used research methods are briefly introduced.

1.3.2 Research questions and chapter overview

The main research question elaborated in chapter 2 has been formulated as:

- *What are the main challenges and practiced approaches to solutions in urban water management in developing countries?*

This theoretical chapter focuses first on the big needs of water supply and sanitation in developing countries and the way urban water management needs to be reconceptualized under the notion of sustainable development. It is shown that in many respects the *business - as - usual* approach of government-led planning and implementation is no longer tenable. The chapter investigates transformations of practices, principles and structural measures that may lead to more sustainable urban water chains. The emphasis is laid on infrastructure upgrading with a strong role of lower governmental units and end-users in planning and design. Accordingly, a need of methods to support this process is identified. This chapter is partly descriptive, partly prescriptive, and based on observations and literature study about the international water supply and sanitation practice. Several of the introduced principles are applied and validated in later chapters.

The research question at the basis of chapter 3 is:

- *What would be an adequate method for planning and selection of appropriate and sustainable drainage and sanitation systems?*

Transparency of decision making and management, and stakeholder cooperation through material chains are found to be necessary institutional transformations on the way to sustainable development (chapter 2). At the same time the analysis of the drainage and sanitation upgrading practice in Ho Chi Minh City demonstrated the need of stakeholder involvement (chapter 8). Consequently, a method of participatory planning and selection of appropriate and sustainable drainage and sanitation systems based on the theory of multi-criteria decision analysis has been developed in this chapter.

In the ensuing chapters 4 until 7 a data base of assessment criteria and indicators (chapter 4), drainage and sanitation system options (chapter 5), the technical, hygienic and environmental performance (chapter 6) and costs (chapter 7) of drainage and sanitation technologies is elaborated. The leading research questions of these chapters are respectively:

- *What are adequate criteria and indicators for the participatory assessment of the appropriateness and sustainability of drainage and sanitation systems?* (Chapter 4);

- *Which are the drainage and sanitation system options applicable in cities in developing countries?* (Chapter 5);

- *What are the technical, health-related and environmental performances and what are the factors that restrict the application of the technologies that together form the drainage and sanitation system options described in chapter 5?* (Chapter 6);

- *What are the investment and operational costs of the technologies that together form the drainage and sanitation options described in chapter 5* (Chapter 7).

The method of chapter 3 and the data base developed in the chapters 4 until 7 are meant to facilitate the process of technology assessment and selection in a situation under study making use of a well-founded performance matrix. Method and data-base have been developed by means of extensive literature and field study.

Chapter 8 is a diagnostic study about drainage and sanitation in Ho Chi Minh City. This study has been undertaken with the following two leading research questions:

- *What are the critical issues and practiced approaches to solutions in water and wastewater management in Ho Chi Minh City?*

- *What are strengths and weaknesses of the actual approaches regarding wastewater management in the city and in what way should they be amended?*

This part of the thesis investigates the critical issues concerning the water chain in the city, starting with a brief survey of water resources and going into detail with regard to the development of water supply, sanitation, sewerage and drainage, wastewater treatment and wastewater reuse. The development of water, drainage and sanitation infrastructure is analysed as a function of developments in the domains of housing and urban planning. An analysis is presented of an important recent urban upgrading project in Ho Chi Minh City. On the ground of this analysis action plans are proposed which briefly sketch possible roads towards improved urban sustainability.

While chapter 8 discusses the wide field of drainage and sanitation in Ho Chi Minh City, chapter 9 focuses on the evaluation of a significant development in environmental upgrading, namely the operation of small-scale wastewater-treatment plants for domestic and public-commercial sewage. This development could lead to a certain degree of pollution abatement and be judged important as long as large centralized plants are lacking. It seemed highly relevant to assess this practice of small-scale plants finding answers to the research question:

- *How small-scale wastewater-treatment systems function and what lessons can be learned about sustainable wastewater treatment in Ho Chi Minh City?*

The plants analyzed had capacities in the range of 5 to 1,500 m^3/d and were situated in Ho Chi Minh City and surrounding provinces. Chapters 8 and 9 are based on study of literature, field trips and interviews in the fields of water infrastructure and housing and on the monitoring of wastewater-treatment plants in Ho Chi Minh City and surrounding provinces of Vietnam. The chapters 8 and 9 of this thesis do primarily have a descriptive nature.

The chapters 10 and 11 are the outcomes of the application of the SANCHIS method, developed in chapters 3 until 7, to planning of drainage and sanitation solutions in Ho Chi Minh City. Chapter 10 demonstrates the use of the screening aids to distinguish between feasible and non-feasible systems, and of the performance matrix for (1) a regular system of flush toilets, settled separate sewers and wastewater treatment and (2) a system using urine-diverting flush toilets, settled separate sewers and wastewater treatment with utilization of recovered urine. The leading research question in chapter 10 is:

- *What are the most appropriate drainage and sanitation systems for Ho Chi Minh City?*

It is argued that the conclusions are not only applicable to Ho Chi Minh City, but to many other Vietnamese cities as well.

In the design of sanitation and drainage systems for specific intervention areas the experiences and opinions of a range of actors, and not only those of experts, are of much importance. Especially, the identification of desirable interventions and the assessment of performance of drainage and sanitation options can not be made by merely a small group of experts. Accordingly, SANCHIS stakeholder workshops play a key role in the participatory multi-criteria decision analysis method. Chapter 11 reports about two workshops in Ho Chi Minh City and proposes recommendations for improvement of the SANCHIS method based on their outcomes. The research questions at the basis of this chapter are:

- *What are the outcomes of the participatory SANCHIS method applied to drainage and sanitation problems in Ho Chi Minh City?*

- *How could SANCHIS be improved based on the experiences of the workshops?*

- *What are the strengths, limitations and perspectives of SANCHIS?*

In chapter 12 finally the main findings of the research are summarized. The chapter evaluates what SANCHIS could contribute to the drainage and sanitation planning practice in developing countries and presents recommendations for further research.

CHAPTER 2 TOWARDS ENVIRONMENTALLY SOUND URBAN SANITATION FOR ALL: CHALLENGES AND APPROACHES

2.1 Introduction

The present chapter reviews the literature concerning the main challenges associated with urban water systems in developing countries and new approaches to meet these challenges. The term ‘urban water system’ refers to one system or a combination of independent subsystems. The system may comprise functional elements associated with the provision of water for various uses, the management of rainwater, the appliances for the use of water and the handling of excreta and wastewater in households, industry and public areas. In addition the urban water system includes the collection, treatment, reuse and disposal of all categories of wastewater and associated solids. The service area and complexity of urban water systems may vary greatly.

The urban water system is taken as frame of reference, because all its functional elements may influence each other and should therefore be regarded as a whole. But since the emphasis of this thesis is on strategies for drainage and sanitation improvement and delimitation of the topic is necessary, water supply, industrial wastewater and particularly the functions of surface an groundwater in the city receive less attention that they would deserve in a veritably integrated approach. With drainage is meant here the collection, transport and disposal of stormwater runoff, and sanitation refers to the adequate handling of domestic wastewater and especially the streams that contain excreta.

This chapter comprises eight sections. Section 2.2 describes the challenges and approaches of worldwide water and sanitation development, indicated as Brown Agenda. Section 2.3 introduces the Green Agenda: the environmental sustainability targets which should be included into the Brown Agenda. Section 2.4 investigates the current weaknesses of drainage and sanitation in developing cities in order to draw lessons for better approaches. Taking shortcomings from the past as point of departure section 2.5 proposes seven important principles on which future urban sanitation programmes and projects could be based. Section 2.6 sketches four transformations to be expected when the proposed principles are applied and 2.7 the consequences to environmental sanitation infrastructure. Section 2.8 briefly mentions the differences between the customary top-down and the proposed participatory multi-stakeholder approach. The conclusions of the chapter are summarized in section 2.9.

2.2 The challenge of access to water supply and sanitation (the Brown Agenda)

Deficient water supply, excreta disposal, drainage and solid-waste management is a major problem to public welfare, economic productivity, individual well-being and health. The burden of this problem is mainly carried by the poor in urban slums and rural areas. According to the statistics of WHO, UNICEF and the WSSCC the number of people in the world with adequate[1] water supply increased from 4,140 million to 4,956 million and the number of people with adequate sanitation from 2,905 million to 3,652 million in the period 1991 – 2000 (table 2.1).

Table 2.1. Past and targeted development of water supply and sanitation coverage in the world (WHO et al., 2000).

	1990	2000	2015 MDG	2025 MDG
World population total (mlns)	5266	6055	7154	7823
Population inadequate water (%)	21	18	9	0
Population inadequate water supply (mlns)	1126	1099	612	0
Population inadequate sanitation (%)	45	40	19	0
Population inadequate sanitation (mlns)	2361	2403	1332	0

Every day during that decade 224,000 people were provided, or provided themselves, with improved water supply and 205,000 with sanitation. Due to the huge global population growth, however, the percentage of people not adequately served dropped only from 21 to 18% in water supply and from 45 to 40% in sanitation. The backlog in sanitation facilities as compared to water supply, indicated as sanitation gap, expresses the greater importance users and providers attach to water, while sanitation does not get the attention it deserves, as the negative impacts of its absence are felt less immediately. The higher costs of sanitation systems may play and additional role (Hutton and Haller, 2004). Though the numbers of new facilities established in the 1990s may seem impressive, they failed to meet the targets.
At the World Summit on Sustainable Development in Johannesburg in 2002 an agreement was reached about new targets, indicated as the Brown Agenda. Taking the year 2000 as a baseline the proportion of people without access to water supply, sanitation and hygiene should be halved by 2015, and access for all be provided in the year 2025 (see table 2.1). These targets imply an effort still bigger than that over the past decades. The target for 2015 signified that worldwide every day between 2001 and 2015 a new group of 290,000 people had to be provided with adequate water supply and a group of 396,000 with improved sanitation.

Adequate sanitation facilities are important for several reasons (Tayler et al., 2003):

- Protection of the population against excreta-related diseases;
- Convenience and privacy for their users;
- Prevention of environmental pollution;
- Positive impact on livelihoods of people with adequate sanitation provisions;
- Positive impact on the economy at city and national level;
- Just, equitable and constructive social relations at community and city level.

[1] Reasonable access to water supply is defined as the availability of at least 20 litres per person per day from a source within 1 kilometre of the user's dwelling; the following sources of water supply are considered adequate: household connection to piped supply, public standpipes, boreholes, protected dug wells, protected springs and rainwater collection. Adequate sanitation systems are among others pit latrines, ventilated improved pit latrines, and (pour-) flush toilets connected to sewers and septic-tank systems (http://www.who.int/water_sanitation_health/mdg1/en/index.html (acc 27-07-2010);(WHO, 2006)).

According to a world-wide appraisal by Hutton and Haller (2004, p 39) the economic gains of improved water and sanitation are huge amounting to between 5 and 11 USD of benefits per 1 USD invested for most sub-regions of the developing world (USD of year 2000). As the positive impacts of sanitation exert their influence at different levels of the society, the various stakeholders involved in water supply and sanitation may give a different weight to the importance of the different impacts. Households will probably find convenience and prevention of pollution in the neighborhood most important, while policy makers at governmental level may stress the importance for public health, economy and better social relations. According to Tayler et al. (2003) stakeholders usually agree that helping people to lead healthy and productive lives and protection of the natural environment are the most important objectives of good sanitation. The implication is that, even if poverty alleviation is not addressed directly, sanitation improvement may help in an indirect way to improve the livelihoods of its beneficiaries and to contribute to a well-ordered society.

With regard to the increased access to sanitation the following conclusions can be drawn. There is an enormous need of new facilities both in cities and rural areas of the South. In the past many programmes and projects have been carried out and efforts are being stepped up under the aegis of the Millennium Development Goals. The present initiatives, deployed all over the world in a multitude of governmental, community-led, private sector and mixed projects, could become more effective than their predecessors as they can draw on their experiences. Despite the importance of adequate provision it is improbable that the Millennium Development Goals will be fully attained. One reason is the sheer size of the challenge: the high population growth and urbanization. Especially the sanitation targets raise doubts, since in comparison to the 1990s close to a doubling of the output would be required in the first 15 years of the new millennium (from 205,000 (1991-2000) to 396,000 (2001-2015) new adequate facilities a day) (Mara and Feachem, 2001). The challenges of reaching the targets of adequate sanitation provision will be reviewed in detail in section 2.4. But not only should a worldwide acceleration in the establishment of sanitation provisions be reached, these new provisions should meet new standards in environmental protection and reduction of the consumption of natural resources. This additional challenge of combining the Green with the Brown agenda is discussed in section 2.3.

2.3 The challenge of environmental sustainability (the Green Agenda)

The modern environmental 'movement' emerged at the end of the 1960s against the backdrop of the huge post World War II economic industrial expansion. This environmental movement soon acquired a strong societal impact. It expanded its concerns from local problems to global issues such as population growth, resource depletion, food security and loss of biodiversity, and the relationships between these issues. According to Carter (2001) environmental political thought offered two important insights:

- The ecological crisis urges a reconsideration of the relationship between humanity and nature
- Resources are finite so that there are material limits to growth.

The crucial question became whether and how world and local economy should be restructured to reconcile the needs of deprived masses in the underdeveloped countries and

future generations and the protection of the environment. Though radical ecologists emphasized the necessity of profound changes of values and the economic order, others proposed a more pragmatic course of piecemeal technological and political interventions. The pragmatic approach obtained its theoretical underpinning with the concept of sustainable development, first introduced in the World Conservation Strategy (IUCN et al., 1980), but given its world-wide political impact with the Brundtland report (World Commission on Environment and Development, 1987).
According to Lafferty (1996) sustainable development is a normative concept used to prescribe and evaluate changes in living conditions. These changes should be guided by four principles:

- They aim to satisfy basic human needs and reasonable standards of welfare for all living beings;
- They aim to achieve more equitable standards of living both within and among global populations;
- They should be pursued with great caution as to their actual or potential disruption of biodiversity and the regenerative capacity of nature;
- They should be achieved without undermining the possibility for future generations to attain similar standards of living and similar or improved standards of equity.

The strength of the concept of sustainable development lies in staking out a common ground to developed and developing countries for seeking a more equitable and environmentally sustainable world order. At the Rio Earth Summit in 1992 the principles of sustainable development became the basis of the Agenda 21 and were translated subsequently to policies in various fields such as protection of biodiversity, climate change and urban development.

For those concerned with water supply and sanitation in the developing world the first two, development-oriented, principles, are a reconfirmation of the objectives they had strived for at local level for several decades, i.e. water supply and sanitation for all (the Brown agenda). The environment-related principles of the Green Agenda, however, spur a revolutionary emphasis on environmental protection and resource recovery. The finitude of material resources, tangible already during the world oil crises of 1973-74 and 1978-79, requires a drastic revision of wasteful practices. Waste output should be minimised in the first place by preventive measures. Wastes, whose generation can not be prevented, should be reconsidered a (potential) resource: the practices of extraction of raw materials from the Earth, converting them to useful products, and discharging resulting wastes into the environment should be transformed to well-controlled loops in which valuable and potentially harmful substances are recovered from wastes and re-utilised.
Recently, the idea of sustainable production and consumption and closing of material cycles has been formulated in the radical cradle-to-cradle principle. The design of products and industrial systems should be such that no waste or downcycled materials of lower quality emerge in any stage of their existence, and on the contrary production supports ecological systems and economic growth (Braungart et al., 2006).

Though the vision of closing material cycles affects the entire realm of production and consumption, urban environmental engineers and managers have a special role to play. Their role regards the last stage of the urban metabolism, where a big part of the urban flows have turned into polluted air, wastewater and solid wastes. Up to now these waste streams are either displaced to places where their harm is not felt, or treated with end-of-pipe systems, which require a considerable input of energy and leave us with reduced flows of still noxious residues. Faerge et al. (2001) have estimated that in Bangkok (Thailand) 26,500 ton/yr of nitrogen enters the city in the form of food, fertilizer, cattle feed and atmospheric deposition, and 24,200 ton/yr leaves the city via the wastewater discharges to the principal river and 1,400 ton/yr in the form of solid wastes. These figures illustrate the importance of wastewater discharges to the urban metabolism. At present urban engineers and managers are confronted with the highly challenging questions: can waste be prevented through dematerialization of production and consumption and by closing material cycles. For technologists the question is: how could closed loops be shaped that use less resources (energy, land, water, chemicals) and add value to the components of wastewater, so that they can be reutilized in agriculture, industry and households? Though perhaps the Brown Agenda could be met with existing technologies, the Green Agenda certainly can not do without new social and technical approaches (EAWAG, 2005).

2.4 Shortcomings of 'business as usual' in urban sanitation

Urban sanitation practice in developing countries may boast of millions of new improved provisions annually, but is criticized for its incapability to reach all-in-need and for depletion of resources and damage to the environment. This incapability, despite internationally avowed targets since 1981, seems to be caused by two interrelated shortcomings: (1) inadequate political and institutional response and (2) inappropriate technical systems.

2.4.1 Inadequate political and institutional response

The first reason of failure to reach all in need has an institutional nature, as the burden of policies, implementation and maintenance in the field of urban infrastructure lies on public (state and municipal) institutions. These institutions are incapable or unwilling to come up with adequate policies and enforce them.

According to Tayler et al.(2003, p 5) formal government-led attempts to deal with urban sanitation tend to take a centralized top-down approach, which first focuses on the production of master plans and subsequently on laying out trunk sewers and main drains.

Many of these formal large-scale schemes fail to meet their objectives in that they are limited in extent and serve just the higher income areas relatively close to city centers.

The top-down government-led approach to sanitation is grounded in the history of infrastructure development in The North. When in cities in Europe in the 19th century increased population densities and consumption of water led to massive contamination of ground and surface water and consequently to disease outbreaks, urban authorities and national governments were pushed to take measures against the worst consequences of pollution (McGranahan et al., 2001, p 88; Melosi, 2001). These authorities started to cover cities with water supply and sewerage grids. Following the same line of action governments and cities in developing countries are now relying on the institutional arrangements that had proved their worth in The North and often were, in rudimental form, already introduced in the colonial times.

A successful role of state and city public institutions in infrastructure development presupposes a set of conditions among which the following are of primary importance:

- Commitment to extend services not only to upper and middle classes but also to the poor;
- An adequate set of laws, by-laws, regulations and policies for urban planning, housing and infrastructure development;
- A clear assignment of responsibilities to the various involved institutions;
- Structurally assured funding of urban planning and infrastructure development;
- Institutional competence in planning, implementation and maintenance.

In many developing cities these conditions were and still are hardly met, which explains the problem of matching the rapid urbanization with corresponding urban planning and development of housing and basic services.

In addition to the large-scale schemes targeted at the urban core areas governmental agencies often run more poverty-directed programmes for underprivileged areas. Several important shortcomings of these programmes have been identified (McGranahan et al., 2001, p 93; Tayler et al., 2003, p 6; EAWAG, 2005):

- Their political profile is low. Sanitation for the poor is not considered of high political and economic importance. Projects are usurped by the wealthy and their time-horizon is short;
- They tend to be supply-driven. Attention goes rather to high numbers of facilities realized than to the preferences of the users, so that facilities are not used as intended or not used at all;
- They hardly take into account the importance of behavioral aspects to the control of diseases;
- Their focus is on investment in new facilities. Measures to set up proper operation and maintenance of the new and the existing facilities are neglected;
- They do not become part of the standard governmental approach but remain isolated;
- Rarely the infrastructure these programmes realize is institutionally and technically integrated into the city-wide infrastructure with the consequence of insufficient support in operation and maintenance.

The lack of sanitation provisions in low-income areas often leads individual households, community groups and local government, sometimes supported by national and international NGOs, to plan and build their own facilities. Though the resulting facilities may respond well to the needs of the users, the informal initiatives in sanitation also have their limitations (Tayler et al., 2003, p 7):

Poor technical standards, resulting in reduced performance and premature failure of facilities;
Tendency to shift problems from a local level to the wider environment rather them solving them completely;
Lack of coordination between the local initiatives and higher-order facilities realized by central providers.

Tayler and co-workers (2003) argue that despite their possible shortcomings these informal activities should not be ignored as they may substantially contribute to better sanitation for the poor.

2.4.2 Inappropriate technologies

The choice of appropriate technologies can be seen as an important element of effective infrastructure planning. Experience shows that the provided drainage and sanitation systems in developing cities often are not appropriate to the local conditions, especially to those of the poor, and inadequate with respect to modern environmental requirements. Sanitation systems in cities of Asia and Africa consist of a mixture or central and on-site systems. A familiar mix could look as follows:

- Flush toilets and combined sewers for runoff and wastewater in the central business district;
- Flush toilets followed septic tanks and soakage pits in the high-income low-density areas, open and covered drains for stormwater;
- Pit latrines in low-income low and medium-density areas;
- Communal toilet systems in (ultra-) high density slum areas.

Household wealth, housing density, water consumption and local traditions to a high degree determine the type of system used. Common on-site systems like pit latrines and flush toilets discharging wastewater to soil via a septic tank may lead to soil and groundwater pollution. The higher the water consumption and the housing density the less the possibilities of on-site treatment of wastewater. Though city developers may see sewerage followed by central wastewater treatment as the most desirable or only possible option and bet on extending the existing systems from their core districts to more outlying areas, this system has several characteristics that make it less appropriate in developing cities.
First, in newly developing peri-urban and low-income areas, especially in poor countries, the following prerequisites for sewerage and wastewater treatment do not exist.

- Homogeneity and stability of the residential settlement with respect to income levels, tenure and the densities of building and population;
- Relatively high population density;
- The availability of (piped) water to flush excreta and other domestic wastes through the sewers;
- Competent institutions and enterprises to plan, implement and maintain the sewer networks and wastewater-treatment plants;
- Acceptable (not too large) differences between the size of stormwater and wastewater flows in the case of combined sewer systems.

Second, sewerage plus central wastewater treatment is an expensive option, whose annual costs are in the order of 200 - 300 USD/household.year. In developing countries such high expenses can only be afforded by a small part of the population in the centres with a high Gross Regional Product. Therefore, unsurprisingly, treatment of sewage is still rare in developing countries, and if treatment is available the plants are often overloaded and malfunctioning (Van Lier et al., 2000; Halalsheh, 2002, p 3). The cost aspects are further detailed in chapter 7.

The system of cistern-flush toilets and centralized sewerage has also been criticized for its negative side-effects to the environment: its consumption of big quantities of high-quality water for toilet flushing, under-utilisation of organic residues and the mere displacement of wastes to surface water, where nutrients and micro-pollutants lead to a steady degradation of ecosystems (Varis and Somlyódy, 1997; Lettinga, 2006).

The shortcomings of the approaches to infrastructure improvement depicted above are to be interpreted in terms of inadequate governance. Accordingly, solutions could be sought in strengthening of governmental and non-governmental organizations involved in infrastructure implementation and in innovative modes of governance, which could lead to the emergence of more supportive environments for the various actors ((McGranahan et al., 2001, p 86). The latter theme will be discussed in the following sections. It should be realized at the same time that the many of the difficulties in directing the urbanization process are rooted in underlying problems of under-development: the poverty of the nation, unequal distribution of wealth among its citizens and all their concomitant problems. Therefore, it is to be expected that strengthening of organizations and new steering mechanisms in drainage and sanitation implementation will achieve their aims only under a regime of general welfare improvement.

2.5 Models and governance principles in sustainable urban water management

Environmental infrastructure can be implemented under different social arrangements, which have been characterized by the idealized *models* of planning, market and collective action (McGranahan et al., 2001, p 84) or by different *forms of governance*: hierarchy, market and networks (Kronsell and Bäckstrand, 2010, p 36). It is evident from the description of the current practice that the planning model, characterized by a top-down or hierarchical approach, is presently the dominant social arrangement in the domain of urban drainage and sanitation. In response to the shortcomings of the hierarchical form of governance in water supply and sanitation both the market model and the collective action model are being advocated. Under a regime of market rationality (also indicated as *demand-driven approach*) users are consumers who are free to choose among the offers by competing private suppliers those sanitary services that meet best with their needs and budget (McGranahan et al., 2001, p 95). In urban drainage and sanitation practice, where households have to be serviced by collective sewerage and wastewater-treatment systems, a *market approach* would probably mean a variety of local collective systems run by private entrepreneurs, and central systems operated by private companies under contracts of the local government. Ideally, the advantage would be low priced services that well match the aspirations of different groups of customers, including the poor. According to McGranahan (2001, p 101) the market model shares many of the weak points of the planning model (*supply-driven approach*) and is promoted by comparing the realities of poor planning with an optimistic vision on what a market approach might achieve. In the same line Gulyani (2001) argues that the demand-driven approach ignores a crucial lesson of experience, namely that lack of institutional capacity, combined with inappropriate institutional arrangements, have been identified as the key causes of failure.
Whereas theoretical and practical considerations should moderate high expectations of market-modelled arrangements in sanitation, local collective action deserves a better judgment.

The term *collective action* designates the work of voluntary associations of users, and organizations that intend to support them (NGOs), in the *bottom-up* realization of infrastructure. While the main actors in the planning model are engineers and public officials and in the market model households and private enterprises, grass-root organizations play a central role in provision of services in the collective action model. In drainage and sanitation collective action, with or without support from local government, may lead to a faster and cheaper realization of infrastructure (Hasan, 2002; Melo, 2005). Presently, community participation, i.e. some form of collective action, is an intended part of most government-led sanitation programmes (see section 8.6). Authorities working at drainage and sanitation interventions, especially in low-income communities, have experienced that they need the input of local citizens. Their contribution may consist of knowledge, labor and money, but most importantly should it lead to public acceptance of new or improved systems. Proponents point at collective action as essential to community strengthening. Where communities are poor and initially powerless to achieve their goals, collective action may lead to empowerment and vice versa. In this view collective action is not so much an instrument to increase the legitimacy of government intervention, but an essential means in a multi-faceted emancipation of underprivileged groups.

Many recent documents concerning the realization of the Millennium Development Goals in sanitation plead for a change from a top-down to a bottom-up approach, or in terms of the models introduced above from hierarchical planning to collective action, e.g.:(EAWAG, 2005; WSP, 2009). The advocated change implies a multi-stakeholder approach in which municipal authorities actively seek cooperation with and stimulate action by the targeted user groups. In addition, environmental sustainability has become a normative point of departure in the implementation of new sanitation infrastructure. Waste should be regarded as a resource and new practices of recycling and reuse be developed. As participation of users and grass-root organizations is often new and not well accepted, a strategy aiming at collective action requires accompanying processes to create an environment in which households and communities are enabled to take initiatives and play their role in sanitation programmes. This thesis investigates in chapters 8 and 11 two programmes in Vietnam which have experimented with the multi-stakeholder approach as proposed by EAWAG(2005). The two tenets of participation and environmental sustainability are elaborated into the following governance principles for sanitation programmes. The principles address an informational aspect in addition to the technical, environmental, financial/economic, socio-cultural, institutional and political aspects of integrated sustainable waste management concept (Van de Klundert and Anschuetz, 2001):

1. Political principle: commitment among government agencies to provision of sanitation to all, including the poorest, and creation of an enabling policy, legal and financial environment for actors involved in sanitation provision;

2. Institutional principle: the creation of effective forms of public-private-community-household collaboration that respond to user demand and draw optimum benefit from the strengths, resources and know-how of the involved partners through sharing of information and open communication;

3. Socio-cultural principle: services have to be provided to all strata of society; users and other relevant stakeholders participate in the process of analysis, planning and

decision-making in order to guarantee sanitation facilities that are accepted and used. In order to make this participation effective these stakeholders have to be empowered through awareness-raising and education;

4. Environmental principle: minimization of the use of resources, prevention of wastes, closing material cycles and reduction of emissions to the environment. New technologies and social practices to bring these principles to effect have to be developed;

5. Technical principle: sanitation planning is based on outcomes of analysis of existing situations and conditions and makes use of appropriate technical solutions. Sanitation system design applies the concepts of spatial and chronological unbundling and integration of different material chains. Mixed sanitation systems may be the result;

6. Financial/economic principle: transparent, equitable and sustainable funding of sanitation investment and operation based on full-cost analysis and cost recovery, and stimulation of material cycles that lead to poverty alleviation.

7. Informational principle: information about all aspects of sanitation practice is collected, and made generally accessible. This is in particular important to a successful cooperation between government, market parties and grass-root organizations (McGranahan et al., 2001, p 112).

Application of these principles will lead to and require transformations of the sanitation planning, implementation and operation practice which are discussed in the next section.

2.6 Transformations in environmental sanitation management

The two principal objectives of sanitation infrastructure development are to help people lead healthy and productive lives and to protect the natural environment (section 2.3).
In order to reach these objectives taking into account the principles mentioned in 2.5 four lines of socio-technical transformation are introduced (see figure 2.1).

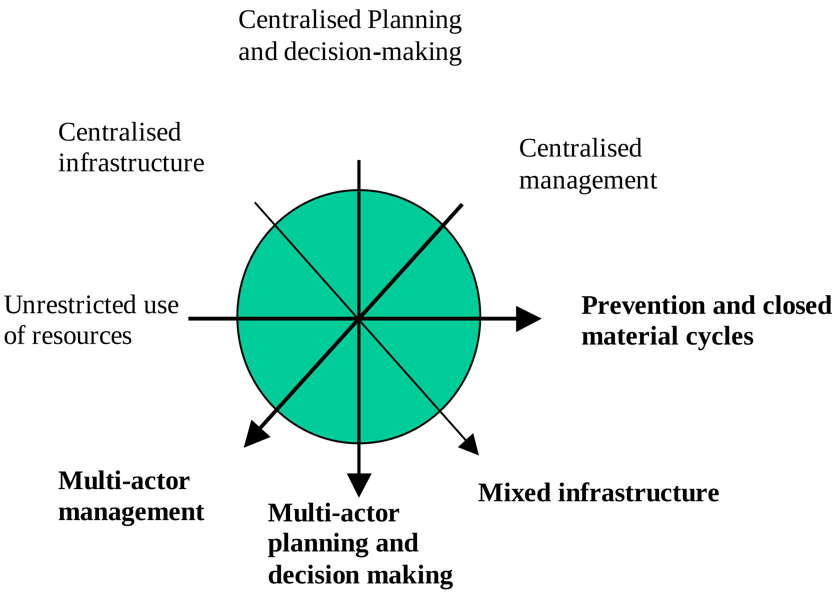

Figure 2.1 Four transformations in infrastructure development.

These transformations depict changes towards co-existence and interaction of the rationalities of the different models described in 2.5, multi-actor management and inclusion of environmental sustainability. They can be characterized as follows:

- Involvement of users collectives and the private sector instead of a purely central provision by the state/city or district (from centralized state-led planning to multi-actor planning and decision-making);
- Shaping of mixed infrastructure management arrangements (from centralized state-led management to multi-actor management);
- Saving resources and reducing emissions through closing material cycles (from unrestricted use of resources to prevention and closed material cycles);
- The emergence of technological mixes according to the conditions of the communities instead of monolithic infrastructure solutions (from centralized to mixed infrastructure).

These transformations of urban infrastructure imply new social practices and technologies. Important questions in this thesis are whether transformations along these lines are observed in reality and whether they deliver the expected improvements. These questions are addressed in the studies about drainage and sanitation in Vietnam reported in this thesis. The four lines of transformation are briefly explained.

1. Multi-actor planning and decision-making in infrastructure development

The monopoly of central public institutions with the resulting *supply-driven* development has been analysed as an impediment in servicing the poor (Gulyani, 2001). A *user*- or *household-centred* approach, following the rationalities of either the market economy or collective action, in which infrastructure development is informed and determined by the preferences and possibilities of the users, is promoted as remedy against failing state plans (McGranahan et al., 2001, p 84). Though all the three models, state-led provision, market and collective action, have their successes to boast about, they all have important limitations. Therefore, Tayler et al, (2003) and EAWAG (2005) plead for hybrid approaches in which each sector builds upon its strength depending on local circumstances. As a cooperation between different parties has to grow in existing situations with their specific physical, institutional and cultural characteristics, it is, however, difficult and even undesirable to prescribe an abstract simplified hybrid model or best practice (McGranahan et al., 2001, p 112, 114). The question in concrete situations is how to combine these different ways of project implementation in order to reach the goals of improved sanitation provision. A common characteristic principle of new approaches is stakeholder participation resulting in multi-actor planning, decision-making and implementation in sanitation improvement (chapter 3, 11).

2. Chain management at household, community and central level

As multi-actor planning and implementation may lead to a mixed infrastructure encompassing various technological systems, the actors responsible for management of these systems do not automatically coincide with the actors who planned and implemented them. The septic tank, for example, is planned and built by the constructor of the house, but its operation presupposes the availability of central (private or public) sludge evacuation and treatment services. The newly emerging material cycles have to be supported by well-functioning institutional arrangements. In rural areas the waste-reuse chain may be operated at the level of the household, but in cities more centralized institutional arrangements will be necessary, as for example in compost production from organic biodegradable wastes. The chain there includes the households who separate wastes at source, composting companies and compost users (farmers, households) and a supervising agency that enforces regulations for the quality of the compost product. Therefore, decentralized technologies may require centralized institutional arrangements.

3. Saving resources and reducing emissions through closing material cycles

To achieve the goals of environmental sustainability, that is saving resources and reducing emissions, several approaches have been suggested that could be combined into an integrated sustainable waste(water) management (ISWM) strategy. An ISWM strategy is based on the outcome of a situation analysis using the ISWM tool (Van de Klundert and Anschuetz, 2001). Due to its multi-faceted nature and purpose ISWM assessment and planning necessitates the participation of stakeholders in several stages of the process.

An important policy principle in the ISWM strategy is the hierarchy of prevention, reuse/recycling and disposal, where prevention has the highest priority followed by reuse and recycling, with disposal as a last resort. A second principle assumes that much can be gained when the waste problems of urban material cycles of food (for humans and animals), non-food agro-industrial products, fertilizers, water (in households and industry) and energy are approached in an integrated way (UNEP, 2009). In addition, the household-centred environmental sanitation strategy recommends solutions of environmental sanitation problems as close as possible to the place where they occur, thus attempting to avoid export of waste problems to other places and strongly advocating on-site and decentral sanitation solutions (EAWAG, 2005).

The principle of waste prevention applied to urban sanitation requires measures to save high-quality water and reduce the use of chemicals that find their way to wastewater in industry and households, to eliminate diffuse pollution sources, to reduce the consumption of energy and chemicals in drinking water supply and wastewater treatment, etc.

The recycling and reuse of wastes instead of disposal is a crucial societal innovation, but often not immediately applicable, since they may require the development and introduction of new technologies and a the acceptance of changed social practices. The same holds for integration of different material chains, such as the chain of food wastes and wastewater in systems where biogas is produced from a mixture of black water and food wastes. A relatively simple procedure such as the recycling of septic-tank sludge for use in agriculture presupposes not only a collection service and an effective and inexpensive technology for upgrading sludge to a sufficient-quality soil-conditioner, but most important a developed effective demand for the product. Fundamentally, reuse requires the cost-effective upgrading of wastes to attractive and competitive products in a real market. In general, the costs of upgrading wastes to reusable products will have to be paid by the polluter, while the benefits accrue to society as a whole. The ultimate test of the efficacy of turning waste to a resource lies in reduced resource consumption and emissions.

4. Emergence of mixes of central and decentral drainage and sanitation systems according to conditions of the communities: spatial and chronological unbundling

To achieve infrastructure coverage that reaches not only city centres and wealthy districts, but also poor outlying areas, the concept of spatial unbundling has been suggested (Niemczynowicz, 1996; Wright, 1997). Water and sanitation solutions are sought that fit all the different types of neighborhoods and housing types of the city. As indicated above these technological mixes do already widely exist in Southern cities and they develop dynamically where environmental infrastructure is spreading to new parts of the cities. The concept of unbundling is illustrated in table 2.2.

While in densely populated higher-developed parts the existing infrastructure of cistern-flush toilets and sewers is improved, extended and equipped with sewage treatment stations with or without effluent reuse, other parts of cities apply a *variety* of on-site and community-based systems. Each potential settlement type (from the first row ‘City center’ to ‘New unplanned areas’) is matched with a selection of wastewater collection, treatment and reuse and disposal possibilities and with an institutional set-up.

Table 2.2. Alternatives for urban sanitation infrastructure as function of settlement type (After: (Niemczynowicz, 1996)). A = applicable.

Type of settlement / Type of drainage and sanitation system	City center	Existing planned suburbs	New planned suburbs	Existing unplanned areas	New unplanned areas
Central sewerage, wastewater treatment, reuse/disposal	A	A	A		
Community- based collection, treatment/ reuse and disposal		A	A	A	
Household treatment Septic tanks Dry toilets Urine diversion			A	A	A

It is clear that spatial unbundling of infrastructure is usually determined by socio-economic factors, though also geographic factors could be a reason for differences of drainage,

sanitation and wastewater treatment/reuse systems. Stepwise upgrading or incremental sanitation development (Kalbermatten et al., 1980) could be called chronological unbundling, a variant of spatial unbundling. According to this concept sanitation infrastructure is improved in stages that follow for example the development of water-supply systems of the households. The challenge to sanitation planners is to implement systems that can be incrementally improved, without the need of completely destroying previously built facilities.
With regard to the most appropriate technologies for decentralized sewerage and wastewater treatment in developing countries experts' views differ strongly. Some conclude that in developing cities only low-tech solutions should be applied (e.g. (Sasse, 1998), while others believe that low-tech solutions do not suffice for environmental reasons and new innovative high-tech mass-produced methods should be developed for wastewater management at community scale(Wilderer, 2001). Here, the interrelationship between technology choice and institutional setting is taken as point of departure. As different technologies require specific institutional forms, the choice of these forms cannot precede the choice of technologies. At the same time however does the choice of technologies emerge from an institutional setting (McGranahan et al., 2001, p 113). An open attitude to new more sustainable technologies apparently requires a willingness to review existing institutional arrangements. The development of a multi-criteria tool for technology selection in this thesis presupposes, that a transformation of drainage and sanitation practice may begin at the side of technology choices, supposing that planners bound to given institutional arrangements will be willing to consider a wider variety of options than they are used to.

2.7 Structural measures for more sustainable urban water chains

In order to achieve (more) sustainable urban water chains four types of structural measures are proposed according to their place in the chain: (1) source-oriented measures directed to prevention of waste(water), (2) measures that reduce the costs of collection and transport of unwanted water, (3) recycling and reuse-oriented measures aiming at utilization of products from waste(water), and (4) disposal-oriented measures.
Generally these measures could lead to important improvements of the current practice, but the significance of the improvements may depend on local conditions, and advantages and disadvantages have to be carefully traded-off.

Source-oriented measures

Saving water
A domestic water consumption at a quantity required for good public health and a convenient life, but without wastage, has many advantages. It limits the impacts of water extraction (water shortages, groundwater depletion) and reduces resources consumption and costs in all stages of the water chain. Less water used leads to less wastewater to be generated and treated. Most savings can probably be achieved in industry, but also over-consumption in the households and public-commercial buildings should be avoided. The application of water-saving appliances in the households (toilets, taps, washing machines etc) and the combat against leakage in distribution networks are important structural measures. Awareness raising about the importance of saving water and financial incentives belong to the non-structural measures.

Environment-friendly toilets
Cistern-flush toilets usually consume about one third of the domestic supply. Using toilets types that reduce the quantities of flush water may lead to a considerable reduction of the material input and costs of domestic water supply and wastewater treatment. In addition, new eco-toilet types may enable reuse of valuable materials in urine and faecal matter and are the first step in resource-recovering urban water chains (Winblad and Simpson-Hébert, 2004). Examples are the urine-diverting flush toilet and the urine-diverting dry toilet. Where no water is used for the transport of excreta, cartage is used instead. The conditions of application of different toilet types is discussed in chapter 6.

Reduction of stormwater runoff flow
Urban areas produce stormwater runoff whose quantities depend on the degree of surface coverage with roads and buildings. Runoff is often heavily polluted and collected together with sewage, so that it requires a sufficient capacity of collection systems and wastewater - treatment plants. Reduction of the quantities of stormwater runoff and its degree of pollution can save collection and treatment costs. It also may positively contribute to the maintenance of natural hydrological conditions. Quantitative reduction can be achieved by harvesting rainwater for useful purposes and enhancing the local storage of rainwater in the underground or in surface basins.

Collection and transport-related measures
In cities collection and transport of wastewater is inevitable. Transport takes place by means of pipes and cartage. These technical transport systems are associated with environmental impacts and considerable financial costs. With regard to piped systems structural measures to mitigate environmental impacts are reduction of infiltration and ex-filtration through better construction. The investment costs of piped systems can be reduced, among other things through the application of the concepts of settled shallow sewerage and condominial sewerage (Reed, 1995; Mara, 1996a; Melo, 2005). Cartage systems are used for the transport of small-flow wastestreams, like septic-tank sludge, and are also proposed for the transport of separately collected urine and faecal matter. Their environmental impacts and costs should be controlled by means of efficient logistics and the use of energy-efficient vehicles.

Resource recovery and closing cycles
The main components of urban wastewater that could be recycled and reused are: water, organic matter and nutrients. Two main structural approaches may be distinguished. The first one is recovery and reuse of components from mixed urban wastewater. This approach does not require separation of waste streams at the household level. A well-known example is the recovery of biogas and the reuse of effluent, including plant nutrients, from central wastewater-treatment plants. By means of estimates of the city-wide nutrient balance it was shown that sewage collection and treatment according to Bangkok's 1995 Masterplan leads to a recovery of 12% of the nitrogen and 19% of the phosphorus flow that enter the city as food, fertilizer, animal feed and atmospheric deposition (Faerge et al., 2001). The remaining nutrients enrich the coastal waters after discharge with wastewater-treatment plant effluent and are practically lost.
The second approach implies recovery and reuse by means of source-oriented measures (Otterpohl, 2001). The basic idea is to separate waste streams at source with the purpose of more efficient treatment and recovery of resources. There are many possibilities to separate

urban wastewater in two, three or four different streams which are separately treated for reuse of its resources. An important implication is the use of innovative infrastructure (toilets, in-house plumbing) at household level. In order to avoid the lay out of more than one large pipe network, these systems seem most appropriate for decentralised applications. These possibilities are discussed in detail in chapter 5 and 6.

Disposal of wastewater
Environment-friendly disposal of wastewater and sludge that cannot be reused requires thorough treatment to minimise emissions to the environment. The degree of treatment is usually determined by official effluent requirements. There is no lack of treatment options (Von Sperling and De Lemos Chernicharo, 2005). The strengths and weaknesses of many of these options are discussed in chapter 6 and 7 of this thesis. The main challenges for developing countries lie in the treatment under the conditions of only partial collection and highly dispersed discharge of wastewater. In this situation, at least for some decades to come, decentralized sewage treatment could be an alternative. The case-study of Ho Chi Minh City elaborated in chapters 8 and 9 of this thesis shows that decentralized wastewater and sludge treatment cope with many serious problems in practice.

2.8 Planning and implementation of sanitation improvement

The process of realization of new or improved infrastructure is described as the project or intervention cycle (EAWAG, 2005; Lønholdt (ed), 2005, p 123). This cycle distinguishes the following phases: (1) project identification, (2) the execution of baseline studies to assess the current situation, (3) the preparation of a project plan, (4) appraisal and approval of project plans after which (5) implementation of works can begin. The progress of works is finally (6) monitored and evaluated to learn lessons for current and future projects. In a top-down approach of sanitation projects this entire process is usually owned and led by a few actors closely related to the municipal government: e.g. by a public works office and a consultant hired for assistance. Other stakeholders may be consulted if necessary but do not play the role of project owners. In a bottom-up approach the most significant differences with the usual project cycle are the initiating role of the beneficiaries (households and their representative organizations), the participation of various stakeholders and the activities to create an environment in which the beneficiaries are supported to act as project owner (EAWAG, 2005). This bottom-up participatory planning and implementation process is evaluated in this thesis on the basis of experiences with two sanitation projects in Vietnam (chapters 8 and 11).

2.9 Conclusions

The improvement of sanitation infrastructure in The South is beset by two major hindrances. First, the burden of infrastructure provision lies on public (state and municipal) institutions whose policies for planning and infrastructure realization and measures of enforcement can not keep pace with the booming urbanization. Second, the applied technical systems are often environmentally inadequate and inappropriate to the conditions of the poor. In order to obtain the breakthrough intended by the United Nations Millennium Development Goals, profound transformations of the sanitation practice based on clear principles are required. These are principles proceeded from concepts of democratic, equitable and transparent governance. The transformation processes require (1) a stronger role for the users and community organizations in planning, decision-making and operation of infrastructure, (2) strengthened cooperation and communication of stakeholders, as part of an integrated approach to the challenges of the urban water chain, (3) adoption of a wide range of on-site, community-based and off-site drainage and sanitation technologies as legitimate options in urban technological mixes and (4) the prevention of wastes and closing of material cycles. Greater environmental sustainability of sanitation systems can be reached through source-oriented, collection and transport-related, resource-recovery and disposal-related measures. As infrastructure improvement requires not only a transformation to increased environmental sustainability, but also a more transparent and participatory planning and decision-making process, a method is needed that enables the stakeholders in infrastructure development to learn about and select the most appropriate sanitation system(s) out of a range of options. Such a method is developed in the following chapters 3 to 7. In chapter 8 and 9 the drainage and sanitation situation in Ho Chi Minh City is reviewed. In chapters 10, 11 and 12 experiences with the suggested principles and methods in the improvement of drainage and sanitation infrastructure in Ho Chi Minh City are shown and evaluated.

CHAPTER 3 THE PARTICIPATORY SELECTION OF ENVIRONMENTAL INFRASTRUCTURE, A LITERATURE-BASED INTRODUCTION TO A METHODOLOGY

3.1 Selection of solutions as part of the project cycle

In solving complicated problems, like the improvement of environmental infrastructure, the following consecutive stages may be distinguished: (1) problem identification, (2) diagnosis, (3) design of solution options, (4) selection of best solution, (5) intervention and (6) evaluation. These 6 stages constitute the project or intervention cycle, depicted in figure 3.1. Situation 1 in this figure is the situation at the outset of the intervention process, while situation 2 is the result in which the problems of situation 1 should have been (partially) solved. The principal questions in the stages of problem identification and diagnosis are respectively: is there really a problem? (identification) and if there is, what causes this problem? For routine problems the intervention cycle can be performed without research, but where problems are to a certain degree unique and routine know-how does not suffice scientific research can be required. The stage of 'design of solutions and selecting the best solution' for the situation under study constitute the decision-making process.

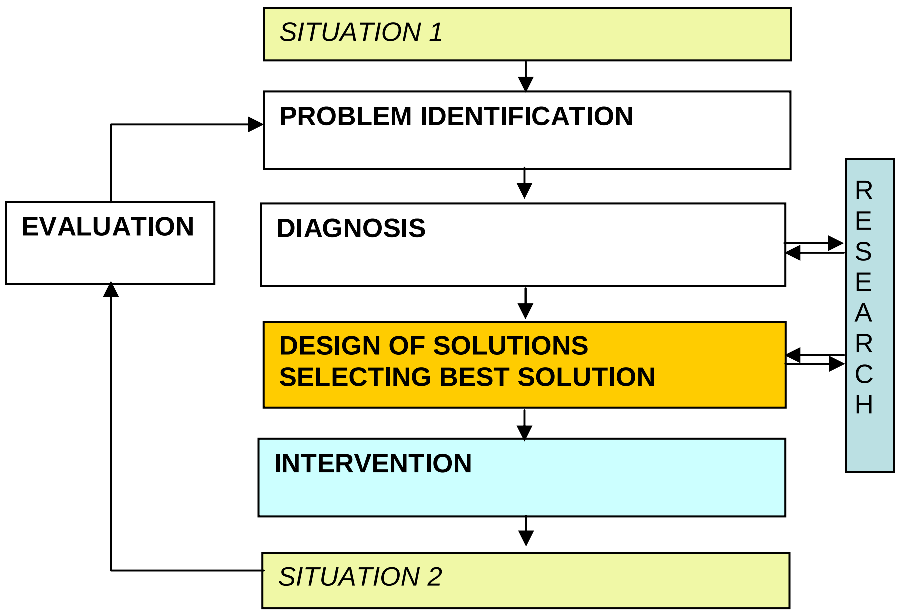

Figure 3.1. The intervention cycle.

While it not uncommon that decisions about infrastructure are made by a small group of planners, technical experts and politicians, the risk of interventions with problematic consequences may be reduced by (1) considering a broader spectrum of options, (2) shaping opportunities for participation of wider forum of stakeholders, including interest groups and citizens, and (3) apply multi-criteria-decision analysis (MCDA) as a rational decision-making procedure in which (1) and (2) are combined. (Lahdelma et al., 2000; Munier, 2004, p 61). Generally speaking, MCDA is a method to make, for a certain situation, the best choice out of several options, where option A scores better than option B with regard to some objectives, but worse on others.

The present chapter consists of three parts: (1) the description of an MCDA method appropriate to decision problems in environmental infrastructure improvement, (2) an introduction to aspects of stakeholder involvement in an MCDA procedure and (3) an assessment of published sanitation decision-support methods. The introduced MCDA method constitutes the basis of the participatory drainage and sanitation decision method named SANCHIS which is elaborated on in chapters 4 until 7 and 10 and 11.

3.2 Decision-making by means of multicriteria-decision analysis

An informed and rational way of preparing and taking decisions includes the following steps (Edwards and Barron, 1994; Loucks and Gladwell, 1998; Lahdelma et al., 2000; Dodgson et al., undated):

- determining the decision context, the stakeholders involved[2] and problem identification;
- identifying the objectives to be reached and criteria and indicators to judge objective attainment;
- identifying alternatives[3];
- data collection about the consequences (criterion-performances) of the system options;
- screening unfeasible options;
- selection of a suitable decision aid to assist in making tradeoffs among the feasible options;
- provide information about preferences (weights given to criteria) of present and future stakeholders;
- calculation of the multi-objective or multi-criteria utilities[4];
- examining results, choosing the most appropriate option, identifying new options;
- sensitivity analysis;
- taking the decision.

The essence of multi-criteria decision analysis can be summarized with the acronym PrOACT (Hammond et al., 1999, p 5):

- **Pr**oblem
- **O**bjectives
- **A**lternatives
- **C**onsequences
- **T**rade-off

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[2] In the literature the participants of an MCDA are indicated as (*key*) *players*, *assessors*, *stakeholders*, *decision makers* and more.

[3] Option is a better word than *alternative*, since alternative refers to the existence of only *two options*.

[4] Several terms are applied for the word *utility*, e.g. *attainment value* and *preference score* (Dodgson et al.). Utility is a key notion in classic economics, where it is a measure of the satisfaction associated with the consumption of goods. It is assumed in economic theory that actors in society always strive and should strive to maximize utility. Utility is for most synonymous with value (Olson, 1995).
The aim of the decision process is to find the option with the highest utility under the circumstances at hand.

Multi-objective or multi-criteria decision analysis can be applied to complicated multi-stakeholder decision problems as there are frequently found in the field of infrastructure, but also for personal decisions in which there is only one stakeholder/decision maker (Hammond et al., 1999).

Since the 1980s the procedure of MCDA is regularly used in infrastructural decisions. Lahdelma and co-workers(2000) mention several MCDA applications in Finland in the field of solid-waste management, power plants, cleaning polluted soil and more. Guerrero Erazo (2003) applies it in the selection of suitable wastewater-treatment systems for Colombian villages. Seghezzo (2004) uses the method in a sustainability analysis of wastewater-treatment options. While in general an important goal of a participatory MCDA procedure is to ensure commitment of stakeholders and legitimacy of the selected option, some (Lahdelma et al., 2000; Seghezzo, 2004) emphasize the advantages of the learning process. In this approach the good decision is seen as a product of the stakeholders' learning process.

The next sections explain the five different stages of multi-criteria-decision processes: (1) identification of problems, (2) formulation of objectives, criteria and indicators, 3) listing of options, (4) making a consequences table (also called performance matrix), and (5) trading off strengths and weaknesses of various options in a situation under study.

3.3 Stages of the multi-criteria decision-making

In the previous section the stages of multi-criteria decision making were listed. Here, a further explanation is given.

3.3.1 The decision context and problem identification

Detailed insight into the decision context and a problem definition can be obtained in several ways of which a baseline study, visits to the intervention area and workshops with stakeholders are common elements. As drainage and sanitation infrastructure has a long lifetime, the development and most probable characteristics of the intervention area in the future (30 years) must be determined at this stage (Dominguez et al., 2008). At the end of this step stakeholders have reached a consensus about the problem under study.

3.3.2 Objectives, criteria and indicators

Values, fundamental objectives and means objectives direct a decision process as conceptualized by Olson (1995). These can be arranged in a hierarchical way as presented in figure 3.2.

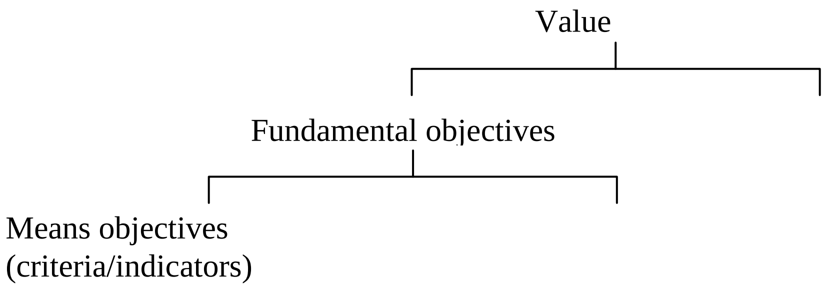


Figure 3.2 Hierarchy of values and objectives directing a decision process (Olson, 1995).

Foxon and co-workers (2002) propose to apply four fundamental *values* (principles) of sustainable development to the water industry. These values are social progress, effective protection of the environment, prudent use of natural resources and maintenance of high and stable levels of welfare growth and employment. These four values represent the essence of sustainability (Lafferty, 1996). *Public health* could be considered as an aspect of social progress and as such as a *value*. A fundamental objective connected to this *value* would be the *healthy city*. *Good sanitation* could then be considered as a *means objective* in the framework of reaching a healthy city. In addition to the word *objective*, it is important to explain the meanings and interrelationships of the words *criterion* and *indicator*. In this thesis the word *criterion* is understood as: 'a parameter used to evaluate the contribution of a technology to meet an objective' (Munier, 2004, p 47). The word *criterion* is also often connected to a certain preferred, or legally set, value, for example in the sentence *the criterion of an efficient septic tank is a COD removal of 40%*. Preferably criteria fulfillment should be assessable by means of objectively verifiable and quantitative *indicators*, such as for instance a removal percentage (%), removed pollutant loads (kg/year) or costs (USD/household.year). An example of the interrelationships between objective, criterion and indicator for septic tanks is shown in figure 3.3. *COD removal* is a criterion for measurement of attainment of the objective of *reduction of the pollution of the effluent*, the *COD removal percentage* is an indicator of COD removal. It is evident in this example that the *objective* is of a higher order than the chosen *criterion* or, in other words objective attainment could be assessed by means of several criteria and indicators. Often quantitative indicators are unavailable and assessors have to satisfy themselves with qualitative or judgmental indicators. An example is the objective of (technical) reliability of a technology about which experts often have quite different opinions, as there are several, often site-specific, indicators that could be used to measure the attainment of this objective. As the selection of relevant objectives, criteria and indicators depends on stakeholders' judgments and the nature of the project under study, there can not be a *once-and-for-all* set, which would serve all selection processes in the field of drainage and sanitation. Wherever a selection of technologies has to be made, decision makers have to come up with an acceptable set of criteria and indicators[5].

In addition to criteria, *factors* are important. If in this thesis criteria are considered parameters to judge objective attainment, factors do affect the degree to which an objective is attained. Accordingly, technology assessment requires an inventory of these factors and of the way they influence objective attainment. Among the factors a further distinction between site-related and technology-related, and restrictive and influencing factors can be made (Philippine Sanitation Sourcebook(2007). Restrictive factors refer to conditions in the situation under study, which allow or do not allow the application of a certain technology in that situation. Restrictive factors are always site-specific, since technology-specific factors that would restrict the functioning of a technology would point at a severe flaw in the design of that technology. Influencing factors have impact on objective attainment, but do not restrict the applicability of a technology: they can be site- and technology-specific. Restrictive factors are especially important in distinguishing feasible from non-feasible technologies (see section

[5] Literature does not always clearly distinguish between objectives and criteria (Hammond et al., 1999) and between indicators and criteria (Sahely et al., 2005). According to Hammond et al. (1999, p 29) '[…] objectives […] form the basis for alternatives open to you. They are, in other words your decision criteria'. In this definition the meaning of a criterion is very close to a (sub-) objective.

3.3.4). The example of the septic tank shown in figure 3.3 may elucidate the above distinctions.

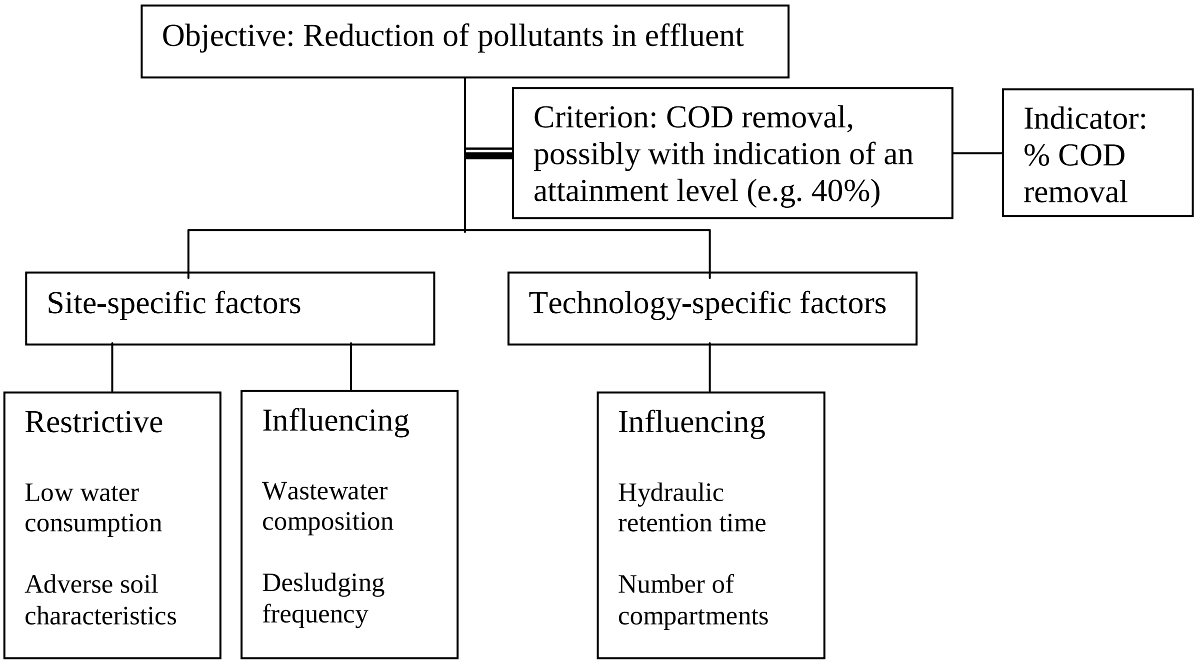


Figure 3.3 Relationship between an objective, an indicator and a criterion and factors that determine objective attainment for the case of septic tanks.

A main objective of septic tanks is to contribute to the reduction of pollutants in their effluent. Restrictive site-specific factors that determine objective attainment are *water consumption* and *soil characteristics*. Where the water-supply system does not enable to use flush toilets, there will be no black water[6] and consequently septic tanks would not be useful. In a rocky soil septic tanks are hard to construct and therefore very expensive, so that a rocky underground could be seen as a restrictive factor. Factors that *influence* the COD removal are the site-specific factors *wastewater composition* and *desludging frequency* and the technology-specific factors *hydraulic retention time* and *number of compartments*.
Some authors (e.g. (Loetscher, 1999)) use the word *criterion* to indicate what is called in this thesis a *factor*. The distinction between criterion (judgment) and factor (causative agent) is however important, particularly in the elaboration of a screening tool. Formulation of objectives, criteria and indicators can be complicated, because it has to fulfill a considerable list of requirements. These are further detailed in chapter 4.

3.3.3 Identifying options

A prerequisite in identifying efficient and sustainable drainage and sanitation systems is insight in the conditions and requirements under which these systems have to serve from now until the end of the system's useful life. There are situations in which these future conditions can be satisfactorily determined through extrapolation of data from the baseline study, but often the future conditions and performance requirements may be surrounded by uncertainty.

[6] See glossary.

In this case drainage and sanitation planners should obtain sufficient certainty, or at least a sufficient degree of consensus among involved stakeholders, about the most probable future conditions and requirements to be assumed in the design of systems. In view to their long design lifetime system options should be sufficiently adaptive and resilient to uncertain changes (Loucks and Gladwell, 1998, p 2, 33). A method to find agreement on technical options under uncertainty of future development is proposed by Dominguez and co-workers (2008) and described below (3.4.1). There are usually several options that could be used in theory. The baseline options are those found in the existing infrastructure. As a first approximation a range of known and potentially viable options could be listed (the long-list). In order to reduce the effort of assessment, the participants in a decision process would wish to eliminate options that are unfeasible in the situation under study as soon as possible. This process is named *screening* and it is based on insight in the prevailing site-specific restrictive factors. After screening the remaining feasible options are compared based on assessment of their consequences in terms of the criteria.

3.3.4 Learning the consequences of options: screening and comparison

3.3.4.1 Screening unfeasible options

Feasible system options are those that are implementable in the situation under study.
There may be conditions in that situation that rule out certain system options. As drainage and sanitation systems usually include a chain of technologies, like a flush-toilet, a septic tank, a sewer and a wastewater-treatment plant, for each technology the restrictive factors in the situation under study have to be found in order to determine the feasibility of the system as a whole.
Restrictive factors are certain site-specific *physical* conditions in the first place. For instance, if the ambient temperature is less than 15^{o} C during a considerable time of the year, high-rate anaerobic reactors are an unfeasible technology for the treatment of sewage. Or, if the soil in the area under study is extremely impermeable and rain intensities high, local infiltration of stormwater is deemed unfeasible. Community-related and household conditions could also be restrictive factors. Legal regulations and policies could prescribe certain system options and rule out others.
Communities may lack the skills to operate certain technologies. End-users may not accept a certain system, e.g. because they find it inconvenient or against their cultural traditions. In some cases the options may not be immediately feasible, but may become so after an adaptation. Decision aids often include algorithms for screening of options. Examples for drainage and sanitation and wastewater treatment are presented in chapter 6 of this thesis. The process of screening can be visualized by figure 3.4.

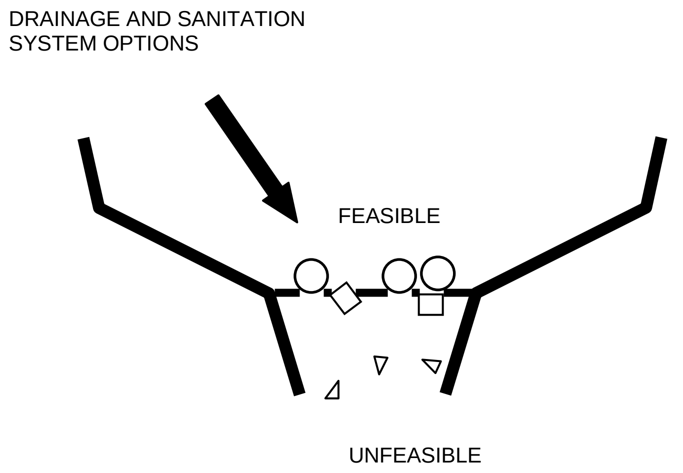


Figure 3.4 Screening feasible from non-feasible drainage and sanitation system options. Circular options are feasible, square ones could be feasible after adaptation, and triangular options are unfeasible.

3.3.4.2 Identifying the consequences of the system options against the criteria

Once criteria and a long-list of feasible system options have been defined a matrix showing the consequences of the options against the criteria (objectives) is made in order to enable the decision makers to assess the performances of the options. This matrix is called performance or evaluation matrix. It is the essence of decision aids. It supports stakeholders to quickly compare the consequences/ performances of various options. The consequences have to be evaluated on the basis of suitable qualitative or quantitative indicators.

Technology-specific and site-specific criteria and performance

As described above the performance of a system option in reaching a certain criterion (objective) is usually influenced at the same time by technology- and site-specific factors. This phenomenon can be visualized by means of figure 3.5.

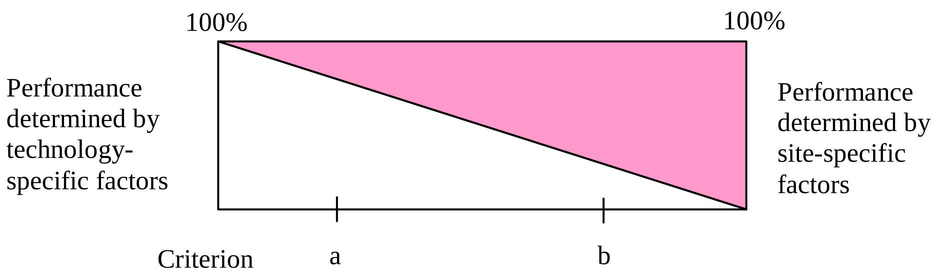


Figure 3.5 Criterion-performance determined by both technology/system-specific and site-specific factors.

The performance of a technology with regard to a criterion ‘a’ (X-axis) is to a higher degree influenced by the technology-specific than by site-specific factors. For criterion ‘b’ the performance of this same technology is more determined by site-specific factors. Example: *low risk of technical failures* could be one of the criteria in the judgment of the *technical functionality* of a drainage and sanitation system. One of the causative agents of technical failures is *clogging of pipes*. The risk of *clogging of pipes* is high where piped systems transport wastewater with a high concentration of solids, and may be reduced by technology-specific interventions like the construction of gullies (rainwater inlets) and interceptor tanks that retain solids from streets and households, but also by site-specific interventions like the increase of the budget for street cleaning and sewer maintenance. This mixture of technology-specific and site-specific influences on system performance makes it impossible or at least unreliable to say which is the best option without taking into consideration the conditions under which an option has to be applied. In the composition of performance matrices for system options it is useful to make a separate assessment with regard to *technology-specific* and *site-specific criteria*, i.e. criteria whose fulfillment is primarily determined by technology-specific respectively site-specific factors. Comparison based on technology-specific criteria may help to find the most appropriate of the assessed system options *independent* of the situation under study, while comparison based on site-specific criteria brings in factors related to acceptance of the system by providers and end-users. This difference between technology- and site-specific criteria in the assessment of drainage and sanitation system options is further elaborated on in chapter 4.

Scoring of options

In order to enable the calculation of utilities[7], the entries of the performance matrix should be reformulated as an attainment value or preference score (u_{ik}). For example: if the land use of the most land-saving drainage and sanitation option in the situation at hand is 0.5 ha and of the most land-using 5 ha, the option with the highest land use is given a rating of 0 and the option with the lowest land use a rating of 100, assuming that low land use is always better than high land use. Through linear interpolation an option with a land use of 1 ha is given the score 89. The utility scores given to indicators should always be expressed such that a higher number is preferable to a lower one. The use of linear utility functions should be justified. In some cases non-linear functions may be recommendable. Since the elicitation of details of utility functions is tedious and their contribution to wiser and more valuable choices is usually negligible (Edwards and Barron, 1994), in this thesis linear utility functions are used only.

As performance for a certain indicator is often determined by several factors, sub-tables may have to be constructed to aggregate indicator values to the criterion- performance score. The score for the criterion *low risk of technical failures* (otherwise named *technical reliability*) of a drainage and sanitation system could be understood as an aggregate of the scores for three sub-criteria and their respective indicators, viz. *avoidance of clogging, independence from external supplies (power, spare parts) and resistance to negligence.*

The reliability of the performance matrix is a function of the degree of subjective judgment and uncertainty in the criterion-performance assessment. The more assessments have a judgmental nature, as for example illustrated by an argument like: ‘I suppose (but I am not certain) that a UASB reactor in the situation at hand is more reliable than an anaerobic filter’, the more uncertainty and inaccurateness creeps into the performance matrix. Performance uncertainties do not have an important influence on the final decision, if the criterion concerned is not given high importance. But if a decision between options appears to hinge upon uncertain performance scores, more study to eliminate these uncertainties (research), or to rationally assess the probabilities of uncertain events (e.g. breakdown of a treatment

[7] Utility: see glossary.

system), is advisable. In general, decision makers should strive at using performance matrices with objectively measured consequences. Future system performances could be simulated by means of statistical models that yield performance scores as a function of time (Loucks and Gladwell, 1998, chapter 4). Often reliable performance data and models are not available, so that a performance matrix should indicate the degree of uncertainty associated with certain performance data. The participants in a decision-making process can take this condition into account during the weighting of the objectives and criteria.

3.3.4.3 Elimination of dominated options

Before proceeding to the trading-off stage absolutely and practically dominated options should be identified and eliminated, so that trading off is carried out with feasible non-dominated options only and the effort during that step of the process is minimized.

An option is dominated *absolutely,* if for all criteria its performance is lower than one of the other proposed options. Since a decision maker would never select a dominated option as the best choice, it should be eliminated from the selection process. There may also be options that have disadvantages in most criteria, but small advantages in one or a few others. If the assessors find that these few small advantages would never outweigh the disadvantages, these options are *practically* dominated and could also be eliminated. Practical domination can also be the outcome of the decision-maker's criteria for objective attainment. Suppose for example that an assessor compares a wide set of dry, water-saving and water-consuming toilets and ancillary sewerage and wastewater-treatment systems with regard to the objective of *social manageability*. Trusting on his knowledge of the local situation he finds that the vacuum-toilet system scores lower on this objective than a required minimum score. He, therefore, eliminates vacuum toilets from the selection process. In this case the aspiration level for the objective *social manageability* is higher than a vacuum-toilet system can achieve. It should be noted, that using practical dominance in eliminating unaccepted options is somewhat judgmental, but can be justified, particularly if the assessor has sufficient experience in the situation under study. Elimination of dominated options can be facilitated by ranking them with respect to criterion attainment. Dominated options, if present, are easily detected in the resulting table: they possess a lower rank on all objectives than one of the other options (Hammond et al., 1999).

3.3.5 Tradeoffs among the options

In order to compare the feasible options the scores on the various criteria have to be combined into an overall preference value. Here, the linear additive model is used according to equation 3.1:

$$U_i = \sum_{k=1}^{K} w_k * u_{ik} \qquad (3.1)$$

Here:

U_i = overall utility (preference) of option i;

w_k = weight (importance) of criterion k;

u_{ik} = performance (preference) for option i on criterion k.

The sum of the weights for all criteria is normalized to 1.0, so that the value of w_k indicates the relative importance of objective 'k' among the total set. As can be concluded from equation (3.1) the overall utility of an option depends on the performances for the various criteria and on the weight given to the criteria.

3.3.5.1 Trading off by making even swaps

The core of MCDA is trading off the disadvantage with respect to one criterion against the advantage with respect to another (Hammond et al., 1999). This is illustrated by a practical example.

Suppose a family (in Vietnam) is building a new house. This house is provided with piped water supply. In choosing a toilet system they consider two well-known options: the pour-flush and the cistern-flush toilet.

The criteria important for the family are low investment cost, low running cost and high convenience. As investment costs for both options do not differ much, it skips this criterion from the comparison. Running cost is mainly determined by the costs of flush water, which costs 0.25 USD/m^3. Taking into account the flush-water volumes of the alternatives running cost would be 0.34 USD/month for the pour-flush toilet and 1.88 USD/month for the cistern-flush toilet. The performance matrix would look as follows (table 3.1).

Table 3.1. Performance table of two toilet alternatives.

Criteria	Pour-flush toilet	Cistern-flush toilet
Convenience	Moderate	Excellent
Running costs (USD/month)	0.34	1.88

The question is: what should this family choose? They could approach this problem by asking: how much would we like to pay more than 0.34 USD/month for avoiding the filling, carrying and pouring buckets of water to flush our pour-flush toilet and improve this toilet's convenience to that of a cistern-flush toilet?

The amount they are willing to pay more for the more convenient system will mainly depend on the value they put to their time and effort. The husband and wife appear to have different views. The husband tends to prefer the pour-flush toilet, because it is cheaper and the wife feels attracted to the more convenient cistern-flush toilet. The wife convinces her husband that she in fact is the most important stakeholder, as she usually has the task to fill the buckets and clean the toilet. The husband agrees that it is fair to let his wife take the decision. After careful consideration the wife feels that 1 hour of her time and effort has a value of 2 USD. She estimates that all activities related to the flushing of the pour-flush toilet costs her 90 minutes/month, which corresponds to a value of 3 USD (90/60 * 2). This implies that she is paying 0.34 + 3.00 USD = 3.34 USD/month for obtaining (giving to her family) the excellent convenience of a cistern-flush toilet. After the even swap the performance matrix looks as shown in table 3.2.

Table 3.2 Performance of two toilet alternatives after having made an even swap with respect to the criterion convenience.

Criteria	Pour-flush toilet	Cistern-flush toilet
Convenience	Excellent	Excellent
Running costs (USD/month)	3.34	1.88

According to table 3.2 a pour-flush toilet costs 3.34 USD/m and a cistern-flush toilet 1.88 USD/m for the same excellent convenience. Since after the even swap the criterion *high convenience* has the same performance for both options, it can be skipped. The comparison shows that the cistern-flush toilet offers high convenience at the lowest cost and the family decides to purchase a cistern-flush toilet. In this example the disadvantage of filling, carrying and pouring buckets was traded off against the advantage of low cost. The most important stakeholder put more weight on convenience (gaining free time) than on the low costs of the flush water for the pour-flush toilet. It is also clear that if time had been valued lower, e.g. due to a lower family income, or if the husband would have been the most important stakeholder, the outcome could have been different. This procedure of trading off is called *making even swaps* (Hammond et al., 1999) or *indifference judgment* (Edwards and Barron, 1994). Although the making of even swaps is the essence of making rational choices, it can be laborious and requiring a lot of information, especially if there are many criteria. A more important challenge, however, is to make even swaps in a forum of many assessors who may have different interests and would make the tradeoffs in a different way.

3.3.5.2 Trading off by ranking and swing weighting

As making even swaps is cumbersome in situations with many criteria, options and stakeholders, a more practical trading-off method is needed. The literature about MCDA presents a multitude of methods with each its specific field of application and its practical and theoretical strengths and weaknesses (Olson, 1995; Lahdelma et al., 2000; Munier, 2004; Dodgson et al., undated). A review of trading-off methods is presented by Olson (1995) and on this basis a method is selected here. The main criteria applied in choosing the method are: user-friendliness, ease in visualizing results and instructiveness. These are the important characteristics since the method should be easily applicable in the setting of a stakeholder workshop with the primary aim of learning about objectives and options in drainage, sanitation and wastewater treatment. In his evaluation of 12 different decision aids Olson (1995) concludes that the methods SMARTS, ZAPROS and VIMDA rank highest in theoretical validity and user appreciation. Since among these three ZAPROS ranks lowest for user-friendliness, and moreover is deemed less suitable for selection problems where there are many criteria to be fulfilled at the same time, this trading-off method was eliminated.

The trading-off method worked out in this chapter is a combination of the principles of SMARTS (Simple Multi Attribute Rating Technique using Swings) (Edwards and Barron, 1994) and VIMDA (Visual Interactive Method for Decision Analysis) (Korhonen, 1988).

According to Edwards and Barron (1994) the weight given to a criterion should not only reflect the importance of one criterion relative to the others, but also the difference of the attainment values among the considered options. If e.g. the cost difference between three feasible wastewater-treatment options is small, say 950,000, 1,000,000 and 1,050,000 USD, or about -5 and + 5% of the average, the weight /importance stakeholders are inclined to give to the criterion investment costs as a factor in the decision will probably be low. This consideration is built into SMARTS by application of swing weighting.

The procedure of SMARTS is explained by means of an example in which four types of biological wastewater-treatment plants in a tropical developing country are compared (table 3.3). The assessors involved judge that high BOD_5 -removal efficiency (E_{BOD}), reliability, low land use and low annual costs are the most important criteria. One might argue that land use is already accounted for in the annual costs, so that using this criterion is a case of double counting. The assessors find, however, that high land use not only has the problem of actual cost, but also of externalities like demolition of existing buildings with its concomitant social unrest and lost opportunities (not yet expressed in money terms) of future alternative use. These two considerations are not expressed by the actual costs and therefore a separate criterion for land use is justifiable. Reliability is scored on the scale: very low, low, moderate, high, very high. Annual costs are normalized figures in which the value for the completely mixed activated sludge process (CMAS) is set at 1 and the costs of other options are calculated in proportion to the costs of CMAS.

Table 3.3 Performance matrix of 4 wastewater-treatment methods.

Criteria	Performance of options			
	Completely Mixed Activated Sludge	Low-rate trickling filters	UASB + submerged aerated filter	Anaerobic and facultative ponds
E_{BOD} (%)	95	90	90	80
Reliability (-)	Poor	Moderate	Moderate	Excellent
Land use (m^2/inh)	0.3	0.6	0.3	1.2
Annual costs (-)	1	0.7	0.6	0.8

In order to make the performance on the different criteria comparable with each other, they are scaled in a way that the lowest performance is given a value 0 and the highest 100. The valuation of the lowest acceptable[8] and highest performances in this example is shown in table 3.4.

Table 3.4 Values of the lowest and highest criterion performances for four wastewater-treatment methods (from table 3.3).

Criteria	Lowest acceptable value (0)	Highest value (100)
E_{BOD} (%)	80	95
Reliability (-)	Poor	Excellent
Land use (m^2/inh)	1.2	0.2
Relative annual costs (-)	1.0	0.6

Performance scores between these values are calculated by linear interpolation, which transforms the table 3.3 to table 3.5.

[8] In the example the lowest criteria performances are taken as lowest acceptable values. If the aspiration values would be set higher, e.g. if *moderate* would be the lowest acceptable value for *reliability* instead of *poor* the option CMAS would be eliminated at this stage since this option is practically dominated by the other options.

Table 3.5 Performance of the options on a 0 (lowest) – 100 (highest) scale.

Criteria	Attainment values of options			
	Completely mixed activated sludge	Low-rate trickling filter	UASB + submerged aerated filter	Anaerobic and facultative ponds
E_{BOD}	100	67	67	0
Reliability	0	50	50	100
Land use	100	67	100	0
Annual costs	0	75	100	50

In table 3.5 the assessors can immediately detect that in the situation under study the low-rate tricking filter can be eliminated from the comparison, since all its attainment values are lower than, or equal to, the values of another option (UASB + SAF). In other words UASB + SAF dominates the low-rate trickling filter.
In SMARTS the weighting of the criteria takes place in two steps: (1) ranking the importance of criteria and (2) assigning the weights of the different criteria on a 0 – 100 scale (swing-weighting). The ranking of importance of the criteria can be obtained by asking the assessors to think about an option that performs badly on all criteria and to decide which criterion's performance would have to be improved first to make this option acceptable? The criterion to be improved first is the assessor's most important one. Subsequently, the question is repeated for the remaining criteria. In this way the assessor's criteria-importance ranking can be found.
Suppose that in our case of wastewater-treatment technologies the assessors could agree on the following ranking: reliability > low costs > low land use > high BOD-removal efficiency.
In the second step, which Edwards and Barron (1994) named swing weighting, the assessors are asked to give values to the importance of all criteria on a scale from 0 – 100. Here, the assessors have to estimate for themselves how the swing of 0 to 100 for one criterion compares to the 0 – 100 swing for another. They should attribute the score 100 to the most important criterion (in this case reliability) and 0 to the 0 – 100 swing of an imaginary criterion that really does not matter. In making these judgments the assessors are encouraged to look at the criterion-differences between the most and least preferred options and how much they care about that difference. If the costs difference of the cheapest and most expensive wastewater-treatment option would be only 10%, the assessors should eventually give a low weight to the criterion of *low costs*, though they would in general consider *low costs* as an important criterion.

The assessors' ranking, swing weighting and the calculated utilities (weighted attainment values) on the basis of the performance given in table 3.5 are shown in table 3.6.

Table 3.6 Calculation of weighted performance values and total scores.

Criteria	Initial ranking	Assigned swing weight	Normalized weight	Weighted performance values of options		
				CMAS	UASB-SAF	A and F ponds
E_{BOD}	4	25	0.1	10	7	0
Reliability	1	100	0.4	0	20	40
Land use	3	50	0.2	20	20	0
Costs	2	75	0.3	0	30	15
Total score		250	1	30	77	55

Examining results and choosing the most appropriate option

The total scores in the above example are 30 for the treatment plant based on the completely mixed activated sludge process, 77 for the UASB-SAF and 55 for the anaerobic plus facultative ponds, and consequently the UASB-SAF is the preferred method. It can be inferred that land-use related factors, expressed in the criteria *low costs* and *low land use*, are decisive in the assessors' preference for this decision process.

3.3.6 Sensitivity analysis

A sensitivity analysis consists of running the procedure again with different values of criterion weight, but in the case of uncertainties also of performance scores. This may help to obtain insight into the influence of different performance scores and criterion weights on the overall scores, and can be especially useful if assessors have different opinions about the input values. Sensitivity analysis can also be important to learn about the effect on a decision of assumed, and potentially different, preferences of future generations. Sensitivity analyses may show that there is not one single best option, but that several options have overall scores in the same range. It often shows as well, that the results are remarkably insensitive to changes in the attributed weights and performance scores. This lack of sensitivity is determined by statistical correlation between performance scores and by the swamping of changes in scores by the other scores for the same option. The latter phenomenon suggests the usefulness of arranging low-level criteria under a higher level main objective and conducting MCDAs for each objective, elucidating the overall scores of the options for each of the main objectives. Then, in a next step, the different scores per objective are combined to find an overall performance score (Dodgson et al., undated).

3.4 Participatory decision-making using multi-criteria decision analysis

3.4.1 Involving stakeholders in a multi-criteria decision process

In chapter 2 the importance of involving all relevant stakeholders in planning and implementation of sanitation improvement was demonstrated. The stakeholder group in sanitation-system selection may consist of decision-makers (local politicians and officials from several administrative sectors), technical sewerage and wastewater-treatment specialists, planners, interest groups, end-users' representatives and end-users proper. In concrete situations the stakeholders can be identified by means of an actor analysis as part of a baseline study (Dominguez et al., 2008). It should be noted that stakeholders may differ with the system options under study. If e.g. cartage of urine is an element of a sanitation system, waste collectors may be an important stakeholder group to be included in the process. Therefore the participating stakeholders should be selected and invited to the process as function of the options under selection.

For participatory decision-making procedures in the environmental field Lahdelma and co-workers (2000) cluster the MCDA phases according to stakeholder categories as shown in table 3.7.

Table 3.7 Phases and stakeholder roles in participatory multi-criteria decision processes (Lahdelma et al., 2000).

Stakeholders	(Phase 1) Define alternatives & criteria	(Phase 2) Make measure-ments	(Phase 3) Choose decision aid	(Phase 4) Provide preference information	(Phase 5) Form draft solutions	(Phase 6) Make final decision
Decision-makers	x		(x)	x		x
Interest-groups	x			(x)		
Experts	x	x				
Planners	x	(x)	x		x	

Once the stakeholders around a certain problem are convened, definition of objectives, criteria and options is the first part of the decision process (phase 1). Selection of feasible options presupposes insight in their consequences. Phase 1 therefore encompasses all steps of the multi-criteria decision analysis except the trading off: the selection of the best option. In this first phase input by all stakeholders is required, i.e. formal decision makers, specialists, interest groups and end-users. It is in this phase that technical experts learn from interest groups and end-users about the conditions under which new infrastructure has to function, while conversely non-experts, such as decision-makers and end-user representatives, learn from technical specialists and planners about the consequences of new infrastructure once established. By jointly formulating objectives and criteria a basis for commitment to the eventual solution is created.

It is to be expected, that during phase 1 no full insight in the consequences of all options can be made available, or that their feasibility can be fully ascertained. Accordingly, data collection about the consequences of options will be required in phase 2 of the procedure. Data collection about the consequences of each system (phase 2 make measurements) is predominantly the task of various kinds of specialists. The choice of a decision aid[9] (phase 3) can only be done by experts. The provision of preference information has to come from the decision makers, interest groups or end-users' representatives (phase 4), while the final (draft) formulation of the conclusions obtained by means of the decision aid is again a task of a specialist (phase 5). The final decision is taken by the formal decision makers (phase 6). Each of these phases needs time and in some occasions a phase will have to be repeated. In complicated decisions especially the collection of data about consequences of options can be difficult and time consuming. Each stakeholder group partakes in the phases where their contribution is deemed most valuable. Experts know the conditions required for technical systems to work (system options and their consequences), while non-experts have a direct interest in and detailed knowledge of the situation for which a solution is sought (problem).

Dominguez and co-workers (2008) describe the method Regional Infrastructure Foresight (RIF) for regional sanitation planning. The process using this method consists of the consecutive phases of Situation Analysis, Scenario Development, Option Evaluation and Presentation of a strategy. The fundamental idea of this approach is the search of a *long-term*

[9] The term 'Decision aid' in the article of Lahdelma et al., (2000) refers to the method for trading off the strengths and weaknesses of the feasible options. In this thesis the term 'decision aid' is used in the broader sense of the performance matrices of options, and support systems for screening and comparison of options in practical situations (section 3.5).

match between sanitation infrastructure and regional development. New sanitation infrastructure that fits well with a present situation may form a mismatch when the region gradually develops into an as yet unexpected direction. The stage of Scenario Development includes the elaboration of scenarios for regional development under different demographic, environmental and economic assumptions, plus different options for sanitation infrastructure. In the stage of Options Evaluation a multi-criteria assessment method is used in which the strength and weaknesses of the options with respect to the different scenarios are evaluated and the most flexible and desirable option is selected. Possible conflicts associated with certain options and scenarios are identified. Scenario Development and Options Assessment are carried out with the aid of two consecutive stakeholder workshops with citizens, industry, regional planners and decision makers.

3.4.2 Strengths and weaknesses of the participatory MCDA method

Although it has become common practice to involve non-government stakeholders in public planning and decision processes, particularly where the environment is concerned, this participatory process comes at a certain cost. Experience has shown that the process does not always deliver the expected favorable results. Here, the strengths and weaknesses of citizen’s participation in public decision processes as evaluated by Bulkeley and Mol(2003) and Irvin (2004) are summarized in table 3.8. In the framework of drainage and sanitation interventions in developing countries citizen’s participation could take the form of the involvement of interest groups (industry), informal sector representatives and end-users or end-user representatives in the decision process. In the assessment a distinction is made between the process itself and its outcomes (Irvin and Stansbury, 2004).

The strengths of participatory public decision making lie in a process in which the various stakeholders learn from each other, may overcome differences in points of view and create new options. With regard to water and sanitation governmental agencies may become better aware of end-user needs and preferences and the conditions under which new infrastructure has to function. This positive process may lead to interventions that are well supported by the involved actors, so that implementation problems are avoided. Moreover, the participants feel that they have gained control over the public decision process and government may increase its legitimacy. Not in all environmental decisions these strengths can be turned into reality. Especially where the problem under debate is complicated and not fully clear, and consensus about the best solution is impossible to be reached, the strengths may not outweigh the weaknesses and the outcome of the process may be unsatisfactory, which may backfire to the public decision makers. It should be noted that a part of the weaknesses pointed out in table 3.8 are not so much an attribute of participatory decision making, but rather of a poor realization of the method. It is of much importance that the initiators of the process (government) clearly delineate the playing field, so that chosen options cannot run counter to governmental possibilities or a framework set by earlier decisions.

Table 3.8 Strengths and weaknesses of citizen's participation in public decision making about the environment (after Bulkeley and Mol, 2003 and Irvin and Stansbury, 2004)

Strengths	Weaknesses
Related to the process	*Related to process*
Learning component and enhanced quality of decision-making	Time and money consuming process, so that less money is available for the interventions
Clarifies different, often opposite views and interests regarding a problem	Methods or organization and the way these processes should be integrated in policy formation are not always clear
Bridges the gap between a scientifically-defined environmental problem and experiences, values and practices of stakeholders	Uncertainty among participants about the problem and the goals to be reached
New options are generated	Difficulty to involve all relevant stakeholders
	A small, very active, group of actors may take over the process
	Consensus cannot always be reached
	Pointless, if the advice or decision is ignored by higher government
	Government may lose control of decision-making process
Related to the outcomes	*Related to the outcomes*
Better policies and interventions	Confusion where benefits of participation are not realized
Establishment of commitment among stakeholders and increasing democratic content	Possibility of a politically unfeasible or environmentally less favorable solutions that government cannot ignore
Avoidance of litigation costs	Bad decisions may result, if heavily influenced by strongly opposing groups

3.5 Decision aids for drainage and sanitation

3.5.1 Introduction to sanitation decision aids

In a participatory process decision aids may play an important role. A decision aid is defined here as a tool that may assist the participants in the decision process in evaluating the appropriateness of the options under study. Decision aids may be designed to cover all, a few phases, or only one phase of the multi-criteria decision process. In this thesis a decision aid is

a tool, that facilitates the screening and comparison of options for a certain set of objectives and criteria under certain conditions of application. Such tools come in several forms.
Here, an overview by Loetscher (1999, chapter 2) is used. Among the decision aids he distinguishes 5 systems as follows:

- descriptive systems;
- check lists;
- decision tables;
- flow diagrams;
- computerized systems.

Check lists are not discussed in the explanation below, since they do not match with the definition of a decision aid used in this thesis.

The first method is the *descriptive system* of textbooks or technical guides. A descriptive system provides for each system option information about its functioning, its requirements, its performance in a range of conditions, its limitations and literature references. An assessor may obtain insight in the feasibility and strengths and weaknesses of different options for a situation under study by comparing the descriptions of the optional systems. Loetscher (1999, p 16) sees as strength of the descriptive system the completeness of the information, but this strength at the same time is its weakness: the user may overlook easily critical information or the descriptions may be too complicated. Examples of such guidelines in the field of sanitation options are Kalbermatten (1982),Cairncross and Feachem (1993), Netherlands Water Partnership (2006), Tilley and co-workers (2008). Information about selection of combined and separate sewer systems can be found in Butler and Davies (2000) and Field and co-workers (2000) and on wastewater treatment in hot climates in Von Sperling and Chernicharo (2005) and Sasse (1998).

A second method are *decision tables*. Decision tables are found in popular consumer magazines in which different brands of cars or digital cameras are compared with regard to a set of criteria. More or less the same has been done for different drainage and sanitation systems. The strength of such decision aids is that they combine objectives and criteria with a set of options and their consequences in a clearly structured table. At a glance the reader can find the option with the best performance. The weakness of relying on decision tables is over-simplification. The method can be a good help where the number of criteria and options is modest, the function of the options is simple and similar, and the decision-maker has sufficient expertise. Usually, decision tables are completed with an explanation of relevant characteristics of the options.
A recent publication on drainage and sanitation systems which combine decision tables with system descriptions are the NETSSAF aid (Zurbruegg and Tilley, 2007) and the Philippine Sanitation Source Book and Decision Aid (PHSSDA, 2007). These publications are discussed in some detail in section 3.6.

A third method are *flow diagrams*. They are used to select one most adequate option from a certain, usually rather small, collection by passing through a series of questions about the situation under which the option has to function. Examples in the field of sanitation are to be found in the work of Kalbermatten and co-workers (1982 , p 51). Loetscher (1999, p 18) calls flow diagrams ‘a problem-related and very well structured approach to evaluation’. But at the same time he judges the method inadequate to complex sanitation problems, since the diagrams would become very elaborate and difficult to read. A danger of the method is also that the user might accept the applied criteria as the only relevant ones in the situation under study. This is in particular relevant if users are non-experts.

A fourth method is *computerized systems*. A recent computerized decision aid in the field of low-cost sanitation is SANEX© worked out by Loetscher (1999).
A strength of a computerized decision system is the possibility to process a large variety of criteria, options and consequences in a structured way, while the software makes the handling of a huge amount of information relatively easy. As Loetscher puts it (1999, p 20): ‘*software hides the underlying complexity of the evaluation algorithm from the user by presenting the criteria one by one and by guiding the user through the evaluation procedure. Also, because inference rules are hidden from the user and executed by the system, they can be far more complex and diverse than what would be possible for the previously discussed types of decision aids’*. According to the author’s experience SANEX© is user-friendly and processes an impressive amount of useful information, but the hidden inference rules often leave the user perplexed why the software judged a certain sanitation option under certain conditions feasible or not feasible. Apparently, the limitation of selection algorithms mentioned above for flow diagrams holds here as well. This disadvantage could be overcome by giving the user access to the hidden layers of the software and by making the software give feedback about the reasons of the selection.

An overview of available decision aids for sanitation from before 1999 is presented by Loetscher (1999, p 21). Examples of more recent sanitation decision aids, all of them non-computerized, are work by Seguezzo (2004) (Wastewater-treatment methods), Mara et al., (2007), the NETSSAF aid (Zurbruegg and Tilley, 2007), the related EAWAG Compendium of Sanitation Systems and Technologies (Tilley et al., 2008), and the Philippine Sanitation Sourcebook and Decision Aid (2007). Only the three last mentioned decision aids include stormwater-drainage systems. They are discussed here.

3.5.2 The NETSSAF sanitation decision aid and the EAWAG compendium

In the descriptions of sanitation systems the NETSSAF aid (Zurbruegg and Tilley, 2007) uses the terms *products*, *processes*, *technologies* and *flowstreams*. Sanitation systems are seen as chains consisting of 6 stages or processes: (1) user-interface (toilets), (2) on-site collection, storage and treatment system, (3) transport, (4) off-site treatment, (5) reuse and (6) disposal.
Products are waste streams like urine, faeces, anal cleansing water, black water[10], grey water and stormwater and mixtures of these waste streams. *Processes* are functional elements in the sanitation chain where waste streams are collected, stored, transported, transformed and disposed of. *Technologies* process a certain product and are found at the intersection of processes and products. A septic tank for example is a *technology* used in the *process* of on-site collection, storage and treatment for the products: black water, black water + grey water, brown water and brown water + grey water. The sequence of technologies applied for the conversion of a product (wastestream) from source to final destination is called a *flowstream*.

[10] See glossary.

Flowstreams can process unaltered products like urine and faeces, but also mixtures of products, such as grey water mixed with brown water[11].
The EAWAG Compendium has been developed as a planning support in the household-centred environmental sanitation strategy using the same systematics as the NETSSAF report. The NETSSAF aid and the EAWAG Compendium offer descriptions of the technologies and technology chains in order to facilitate system comparison. The NETSSAF aid distinguishes 7 sanitation system options and 11 flowstreams, of which 10 are discussed in detail. This aid assesses 75 technologies with regard to 30 criteria. The EAWAG Compendium categorizes 8 sanitation systems including 53 technologies. Both publications present technology-specific advantages and disadvantages, but in contrast to the NETSSAF aid the Compendium does not attempt to give quantitative assessment about technologies and systems.

3.5.3 The Philippine Sanitation Sourcebook and Decision Aid

The aid published as The Philippine Sanitation Sourcebook and Decision Aid (PHSSDA, 2007) is constructed along the same line as the NETSSAF method. The area of application of PHSSDA is limited to low-cost options. It encompasses 5 dry (non-water- reliant), but only 1 wet (water-reliant) toilet option, namely the pour-flush toilet. The options for domestic wastewater are subdivided in 3 categories: (1) non-water-reliant sanitation system for domestic wastewater, (2) water-reliant sanitation systems for domestic wastewater, (3) ecological sanitation systems for domestic wastewater. The latter category contains the options that employ dry urine-diverting toilets. Wet urine-diverting toilets are not discussed in PHSSDA. The total number of technologies assessed is 39, but only 23 of these options are presented in detail.

In contrast to the NETSSAF aid and the EAWAG Compendium, PHSSDA proposes a screening mechanism in which technologies are matched with a list of 6 site-specific restricting variables, which help in deciding, whether a technology would be feasible or not in the situation under study. The comparison of technologies under PHSSDA makes use of influencing variables (characteristics), subdivided into 13 technical non-site-specific and 8 site-specific, so-called demand, variables. The aid assesses the performance with regard to 13 technical criteria of 5 dry toilet options, 1 wet toilet option (PF toilet) for individual households combined with 2 on-site treatment systems (septic tank and aqua privy), 1 wet community toilet option combined with three on-site treatment systems. In addition, the performance matrices contain a judgment of 3 collection systems of faecal matter from dry toilets, 3 sewerage systems, 12 wastewater-treatment options and 4 faecal-sludge treatment options. The sewerage and wastewater-treatment options are not assessed as part of a flowstream as in the case of the NETSSAF aid, so that it is for instance not clear whether the assessment regards the transport and treatment of combined sewage, domestic wastewater or grey water. Such differences may be crucial to the judgment of the technologies. The assessment of demand variables, such as consumer attitude, motivation and desires, PHSSDA considers site-specific and therefore can only be carried out by stakeholders in concrete situations.

[11] See glossary.

Table 3.9 Overview of the drainage and sanitation system options and involved flowstreams in the NETSSAF aid (Zurbruegg and Tilley, 2007, p. 5) and the Philippine Sanitation Sourcebook and Decision Aid (PHSSDA, 2007).
(■ = flowstream is included in decision aid; (■) = technologies are included but not as component of the indicated flow stream)

Nr.	Sanitation System	Flowstreams	NETSSAF	PHSSDA
1	Wet mixed black water and grey water system with off site treatment	Black water mixed with grey water Faecal sludge	■	(■)
2	Wet mixed black water and grey water system with decentralized treatment	Black water mixed with grey water Faecal sludge	■	(■)
3	Wet on-site black water system	Black water Grey water Faecal sludge	■	(■)
4	Wet urine diversion system	Urine/ yellow water Brown water mixed with grey water Faecal sludge	■	
5	Dry excreta and grey water separated system	Excreta Grey water	■	■
6	Dry urine, faeces and grey water diversion system	Urine Faeces Grey water	■	■
7	Dry excreta and grey water mixed system	Excreta mixed with grey water	■	

3.5.4 Assessment of the NETSSAF and PHSSDA sanitation decision aids

The sanitation decision aids NETSSAF and PHSSDA both use an approach in which technology sequences for different domestic waste(water) streams are presented and assessed systematically. The strength of the assessment of technology chains (flowstreams in the terms of the NETSSAF aid) is that rather easily the best combinations of technologies for a certain wastewater type can be selected, once the assessor has indicated the relative importance of the criteria. NETSSAF has a wider scope than PHSSDA as it includes 75 technologies, while PHSSDA assesses 39. PHSSDA is more limited to low-cost sanitation systems. Neither of the aids pays attention to options in stormsewer infrastructure. Stormsewers are merely regarded as technology for the co-transport of certain wastewater streams. Table 3.9 presents the technology chains included in the assessment systems of NETSSAF and PHSSDA. This table shows that the two aids treat the options (5) excreta and grey water, and (6) urine, faeces and grey water as waste(water) streams in the same way. For the other options NETSSAF is far more systematic than PHSSDA, as it rigorously maintains the distinction between the technology sequences for different types of wastewater, where PHSSDA judges technologies for domestic wastewater streams irrespective of their composition (black water mixed with grey water, black water and grey water separated).

With regard to the technology assessment NETSSAF uses technology-specific criteria only and has no mechanism to make a preliminary screening between feasible and non-feasible technologies. PHSSDA includes separate stages of screening and comparison. PHSSDA

additionally discusses the significance of site-specific criteria whose option performance depends on local conditions. Both aids leave the comparison of full sanitation systems (the combination of flowstreams) to the assessors. As a multitude of choices is involved, this full comparison requires much expertise, particularly regarding sewered systems.
The NETSSAF aid, the EAWAG Compendium and PHSSDA each have their strengths and weaknesses. The biggest advantage of NETSSAF over PHSSDA is its rigorous application of the flowstream approach to all waste(water) streams under study (see table 3.9). Consequently, this aid appears more coherent and reliable than PHSSDA. The NETSSAF aid and the EAWAG Compendium visualize well the many technology options in the various sanitation systems. They seem especially useful where experts have to select individual technologies as part of technology chains (flowstreams), as for each involved chain a most appropriate set of technologies can be chosen. In contrast to the NETSSAF aid the EAWAG Compendium has no multi-criteria assessment tool. In the practice of making a system choice in stakeholder workshops this does not have to be a disadvantage, since it is very instructive for stakeholders to work out their own criteria list and make their own assessment on the basis of the descriptions of strength and weaknesses. An advantage of PHSSDA is its screening tool. Such a tool is important in order to help assessors in reducing the number of options to be compared and consequently the effort of the assessors.

3.6 Terminology choices

This thesis makes the following choices with regard to the terminology: a type of wastewater at source (urine, faeces, etc. in the household) is a *source stream*, a type of wastewater during storage, transport, treatment and reuse is a *wastewater stream* or a *waste stream*. A wastewater stream may consist of one source stream or a combination of source streams. The word *technology* is used to indicate a functional element in the processing of a wastewater stream. A sequence of technologies for a certain wastewater stream is named *technology chain*. The word *flowstream* introduced by Tilley and Zurbruegg (2007; 2010) is not used, as it can be easily confused with *wastewater stream* and is difficult to translate in other languages.

3.7 Epilogue

This chapter introduces the method of multi-criteria decision analysis to support decisions in the field of drainage and sanitation infrastructure and the application of this method in the context of participatory planning. It ends with an overview of several published decision aids. It can be inferred, that the requirements to an aid depend upon the context of the process in which it is used. In general one could expect that the higher the level of expertise among users, the more complex a decision tool can be. The complexity increases with the number of options and criteria to be assessed and with the degree of accuracy with which option performance is estimated. On the basis of the methodology presented in this chapter in the next chapters 4 – 7 a decision aid named SANCHIS is developed for urban situations with a focus on Vietnam. This implies that the emphasis is central and community-based off-site systems with piped stormwater and sewage transport. To widen the view of the users of this decision aid several innovative reuse-oriented options have been included. Experiences with the use of this decision aid are reported in chapters 10 and 11.

CHAPTER 4 CRITERIA AND INDICATORS FOR THE ASSESSMENT OF THE APPROPRIATENESS AND SUSTAINABILITY OF DRAINAGE AND SANITATION SYSTEMS

4.1 Introduction

An essential stage in the construction of drainage and sanitation infrastructure in new housing areas, and in improvement in existing areas, is the selection of an appropriate and sustainable drainage and sanitation system. In chapter 3 a method of participatory multi-criteria drainage and sanitation system selection coined SANCHIS was formulated. It was shown, that during a SANCHIS selection procedure the stakeholders compose performance matrices based on a list of system options and criteria for the assessment of the appropriateness and sustainability of these options. The stakeholders subsequently use these matrices to reach a rational decision. In the present chapter 4 a set of criteria and indicators for the assessment of drainage and sanitation systems is selected. This set is used as a guideline for the description and comparison of technologies and technology chains in chapter 6, 7 and 10 and may serve as a resource to stakeholders during a SANCHIS selection process. Section 4.2 presents the requirements multi-criteria decision analysis puts to criteria and criteria sets. Section 4.3 makes a selection of the main objectives, sub-objectives and criteria applicable in drainage and sanitation system selection. These two sections are based on a literature survey. Section 4.4 summarizes the selected SANCHIS criteria set in the key tables 4.8 and 4.9. In section 4.5 the indicators associated with the selected criteria are proposed and discussed. A summary of the chapter is given in 4.6.

4.2 Requirements to criteria

According to the theory of multi-criteria decision analysis discussed in chapter 3 a distinction is made between three categories of criteria: site-specific screening criteria, technology-specific comparative and site-specific comparative criteria. The identification of criteria for systems assessment can be carried out in several ways: through interviews, stakeholder discussions, and literature study (Loetscher, 1999; Dodgson et al., undated). The latter two methods are used in the present study. The final assembly of a criteria list is carried out in an argumentative way (Hellström et al., 2000). Criteria, individually and as the set used in systems assessment, have to fulfill certain requirements which are discussed here.

4.2.1 Requirements to individual criteria

The criteria should comply with two requirements: usefulness and measurability (table 4.1). Useful criteria judge the attainment of objectives of the systems under study. Usefulness of the criteria applied during a SANCHIS selection procedure is guaranteed by the involvement of stakeholders and by the availability of well-considered sets of criteria for drainage and sanitation assessment that stakeholders can use as a resource (tables 4.8, 4.9 and 4.10). Measurability presupposes that the criteria are adequately defined and provided with one or more clear-cut indicators that lead to a reliable and valid quantitative or qualitative judgment (Dodgson et al., undated, chapter 5). With the requirement of measurability the objectivity of judgment is at stake.

Table 4.1 Requirements to criteria in multi-criteria decision analysis.

Requirements to individual criteria	Requirements to sets of criteria
▪ Usefulness ▪ Measurability	▪ Completeness ▪ Avoidance of redundancy ▪ Avoidance of double counting ▪ Mutual independence of preferences

4.2.2 Requirements to sets of criteria

An operational *set* of criteria to assess system options' performance has to comply with several additional requirements as listed in table 4.1 (Dodgson et al., undated, chapter 5). These requirements are briefly detailed below.

Completeness and avoidance of redundancy

A set of criteria should enable to evaluate all relevant aspects of the performance of system options under study. The set should, however, be as concise as possible, since the bigger the set of criteria the more huge the effort of options assessment, particularly if the number of options is large. Therefore, redundant criteria should be eliminated. A criterion is considered redundant if it covers (more or less) the same area of judgment as another criterion in the set, and if it is relatively unimportant. Less important criteria can be identified by making an importance ranking: only the most important ones are included in the set for option assessment.

Avoidance of double counting

Double counting occurs when the effect of a certain factor on option performance is counted more than once. E.g. *land use* of a wastewater-treatment plant is a factor with impact on the criterion *life-cycle cost* of sanitation systems (expressed as USD), but *land use* (expressed in m^2 or m^2 per m^3/d treated) could also be included as an independent criterion in option assessment. If the land use of a project is coming to expression in both criteria, this factor gets overweight in the performance assessment. In this case double counting is avoided by eliminating land cost from the calculation of *life cycle cost* or omitting the criterion *land use* from the criteria set.

Mutual independence of preferences

The different criteria should be independently assessable. It must be possible to assign a performance score to a criterion without having to look for the performance score of one of the other criteria for the same option. A lack of mutual independency could distort the comparison of options by means of the overall preference value or overall utility (section 3.3.5).

4.3 Literature survey

4.3.1 Main objectives

Decision support systems usually group criteria under the heading of an overarching main objective, especially when their number is large. In organizing criteria Loetscher (1999, p 58) introduces the notions of *internal homogeneity* and *external heterogeneity*. This means that a common main objective brings sub-objectives or criteria together into one cluster (internal homogeneity), while the different clusters should be clearly distinguishable (external heterogeneity). In table 4.2 the main objectives under which eight water-related decision support systems have grouped their criteria are summarized: they are technical functionality (T), Health (H), Environment (Env), Social manageability (S) and Economy (E).

Table 4.2 Main objectives derived from water-related decision aids.

Ref. Nr	Reference	Field of interest	Main objectives
1	(Zurbruegg and Tilley, 2007)	San (LIC)	T, H, Env, S, E
2	(PHSSDA, 2007)	San (LIC)	T, H, Env, E
3	(Sahely et al., 2005)	DWS (HIC)	T, Env, S, E
4	(Seghezzo, 2004)	WWT (HIC, LIC)	T, Env, S, E
5	(Van der Vleuten-Balkema, 2003)	UW , WWT (HIC)	T, Env, S, E
6	(Foxon et al., 2002)	DWS (HIC)	T, Env, S, E
7	(Hellström et al., 2000)	UW (HIC)	T, H, Env, S, E
8	(Loetscher, 1999)	San (LIC)	T, S, E

<u>Fields of interest</u>
San = Sanitation HIC = High-income countries
UW = Urban water LIC = Low-income countries
DWS = Drinking-water supply

These eight references have different fields of interest. Three of them are specifically designed for selection of sanitation systems in developing countries. These are the publications by Zurbruegg and Tilley (2007), the Philippine Sanitation Source book and Decision Aid (2007), and the thesis of Loetscher (1999). The others have a different or broader scope. None of them focuses on sewerage and stormwater drainage. Drainage is usually included in the domain of sanitation without however paying much attention to it. All decision support documents mentioned in table 4.2 have the main objectives technical functionality, social manageability and economic desirability in common, though worded in various ways. With the exception of the SANEX© tool developed by Loetscher (1999), which focuses on low-cost sanitation, the other seven aids include criteria concerning prevention of emissions to the environment. Health criteria are not generally included. Loetscher explicitly rejects health protection as an objective, as *all* sanitation options should comply with health and hygiene standards, so that according to him the criterion *health* would not discriminate between the various system options and could accordingly be omitted (Loetscher, 1999, p 59). The list of Hellström and co-workers (2000) and the latest sanitation aids (PHSSDA, 2007; Zurbruegg and Tilley, 2007), however, include one or more health-related criteria. In this thesis the five main objectives of appropriate and sustainable drainage and sanitation systems proposed by Zurbruegg and Tilley (2007) and Hellström (2000) will be used: (1) technical functionality, (2) health protection, (3) environmental protection and resource recovery, (4) social manageability and (5) economic desirability. In the next subsections 4.3.2 until 4.3.6 a selection is made of useful and measurable criteria for drainage and sanitation assessment ordered under the abovementioned five main objectives. These criteria have been derived from five publications listed in table 4.2 that include the assessment of sanitation infrastructure. The criteria from publications that discuss merely drinking-water supply or wastewater treatment are left out of the review. As set forth in chapter 3 a distinction can be between screening and comparative criteria and between site-specific and technology-specific criteria. It is argued in this thesis that screening criteria are found only among the technical-functionality related criteria. Accordingly, the discussion about technical-functionality related criteria below is subdivided in a part about screening criteria and comparative criteria. The criteria listed in the tables below are qualified by indicating their technology-, site-specific or mixed character. Fulfillment of 'mixed' criteria depends on a combination of technology and site-specific factors. A typical example of such a 'mixed' criterion is *costs*.

4.3.2 Technical-functionality related criteria

In the selected literature the technical-functionality related criteria listed in table 4.3 could be identified.

Table 4.3 Technical-functionality related criteria for sanitation systems

Reference	Technical-functionality related criteria
(Zurbruegg and Tilley, 2007)	3 technology-specific criteria: *Simple construction and low level of technical skills* *Robustness and long lifetime* *Simple operational procedures*
(PHSSDA, 2007, p 29)	1 mixed and 4 technology-specific criteria: *Feasibility*[12] *Ease of construction* *Simplicity of operation* *Robustness* *Flexibility*
(Van der Vleuten-Balkema, 2003, p 24)	5 technology-specific criteria: *Maintenance* *Reliability* *Robustness* *Adaptability* *Waste*
(Hellström et al., 2000)	1 mixed and 2 technology-specific criteria: *Performance* *Robustness* *Flexibility*
(Loetscher, 1999)	2 mixed criteria: *Implementability* *Sustainability*[13]

Discussion

Among the technical-functionality related criteria a distinction is made between screening and comparative criteria.

[12] The PHSSDA decision aid uses 6 restrictive factors (parameters) that determine system feasibility, namely: nature of the area, flooding in the area, groundwater level, soil permeability, vehicular access to facilities and space (PHSSDA, 2007, p 29).

[13] Sustainability is defined by Loetscher (1999) as being able to function well until the end of the technology's design lifetime. Its attainment depends to a large extent on site-specific factors: community involvement and motivation, community needs and factors related with adequate operation and maintenance.

Screening criteria
Technical functionality can be achieved only if the individual technologies of a system and the drainage and sanitation system as a whole match with the conditions of the situation under study. PHSSDA (2007) has the criterion *feasibility* and Loetscher (1999) uses *implementability* (table 4.3). In this thesis these criteria are combined to *compatibility with the situation under study* and *compliance with the local policy framework*. These are the screening criteria number 1 and 2 shown in table 4.8. Fulfillment of these two criteria decides about the feasibility or non-feasibility of the system option under study. The fulfillment of the first criterion is determined by site-specific physical and infrastructure-related restrictive factors, such as climate, rainfall regime, soil conditions, housing density, etc. Fulfillment of the second is seen as a prerequisite for system choice, since technologies and systems that do not comply are deemed inappropriate.

Comparative criteria
Technical functionality can be strengthened or weakened by several site- and technology-specific factors. For comparison of drainage and sanitation technologies and systems the shared criteria of at least two decision support systems in table 4.3 are:

- Simple construction and low level of technical skills (2)[14]
- Simple operational procedures (2)
- Robustness (4)
- Flexibility or adaptability (3)

The attainment of the first two criteria *simple construction and required low level of technical skills* and *simple operational procedures* are predominantly determined by technology-specific factors. These two criteria discriminate for example between simple household and communal on-site treatment and the more complicated sewered off-site options. Among wastewater-treatment technologies there are also strong differences with respect to these criteria. Notably, these criteria are used in the decision aids that focus on low-income countries. The criteria seem especially relevant in situations where drainage and sanitation is realized under a regime of community self-help and where there is a probability of irregular maintenance. Though the *level of skills in construction* and *in operation* do come to expression in the operational costs of a system and for that reason could be omitted to avoid double counting, they are nevertheless mentioned as separate criteria number 3 and 4 (table 4.9) by virtue of their effect on the reliability of the system. Their importance depends on the situation under study.
Robustness as an attribute of a technology could mean sturdy, durable and resilient. This criterion is mentioned by four of the five reviewed publications. Robustness is mainly determined by technology-specific factors, such as simplicity of the process, absence of equipment that could breakdown easily, durability of the construction and in the case of wastewater-treatment facilities by long hydraulic retention times. Here, *low sensitivity to irregular maintenance* is considered the main measurable characteristic of robustness. Accordingly, in this thesis this criterion is adopted as criterion number 5 in table 4.9. One other criterion for reliability is added namely number 6 *independence of external supplies (e.g. power and chemicals) and services*. The criteria 3 until 6 determine the reliability of the

[14] The number in parentheses (2) indicates the number of references which share the indicated criterion.

system, which is considered as a sub-objective of the main objective of technical functionality. The criteria *flexibility* and *adaptability* refer to the efforts or rather costs needed to modify an infrastructure system when new conditions occur or requirements are set. Accordingly, the criterion is rephrased to *ease of adaptation to new conditions and requirements* under the sub-objective of *flexibility* (number 7). On-site and community-scale systems are more flexible than large-scale piped transport, treatment and reuse systems. Cartage is easier to modify than piped transport systems.

Selected technical-functionality related criteria
In correspondence with the arguments given above the following technical-functionality related criteria are proposed for the criteria set in this thesis (tables 4.8 and 4.9, criteria 1-7):

Screening criteria
- Compatibility with local physical and infrastructure-related conditions
- Compliance with the local policy framework

Comparative criteria
- Low level of skills needed in construction
- Low level of skills needed in operation
- Low sensitivity to irregular maintenance
- Independence of external supplies and services
- Ease of adaptation to new conditions and requirements

The indicators for measurement of criteria fulfillment are detailed in section 4.5.

4.3.3 Health-related criteria
The review of five sanitation decision support systems yielded the following health-related criteria (table 4.4).

Discussion
Apparently the health-related criteria for sanitation systems have received less attention than the technical criteria in the studied decision support systems. The NETSSAF aid (Zurbruegg and Tilley, 2007) is most detailed about health-related criteria. A strength of the criterion *reduction of exposure* is its distinction between impacts on four categories of stakeholders: end-users, waste workers, resource recoverers and downstream population. The criterion is relevant to evaluate differences between sewerage and cartage and reuse systems and between different types of treatment technologies.
The criterion *hygienization rate* is referring to the contribution of different technologies to the degree of disinfection of wastewater streams. In NETSSAF this criterion discriminates between different treatment technologies. A low degree of hygienization in faecal sludge treatment is for example attributed to settling ponds and a high degree to co-composting (Zurbruegg and Tilley, 2007, p 51). The attained degree of disinfection depends on technology-
specific factors like hydraulic and sludge retention time, reaction temperature and anaerobic or aerobic treatment conditions.

Table 4.4 Heath-related criteria for sanitation systems

Reference	Health–related criteria
(Zurbruegg and Tilley, 2007)	3 technology-specific criteria: *Reduction of exposure to four categories of stakeholders* *Hygienization rate* *Increase of health benefits*
(PHSSDA, 2007, p 29)	1 technology-specific objective: *Health implications*
(Van der Vleuten-Balkema, 2003, p 24)	None
(Hellström et al., 2000)	2 mixed criteria: *Risk of infection* *Number of accidents in the working environment*
(Loetscher, 1999)	None

The criterion *increase of health benefits* judges the system's contribution to improvement of overall public health, like reduction of diseases and an improved food situation through reuse of nutrients in agriculture. This criterion discriminates between disposal into surface water (negative) and reuse (positive).
The NETSSAF criteria *reduced exposure*, *hygienization rate*, and *increase of health benefits* do not seem mutually independent and therefore a reduction of the number of health-related criteria to one criterion is proposed here: *reduced exposure*. *Hygienization rate* comes to expression in *reduced exposure* to waste workers, waste recoverers and downstream population, while *increase of health benefits* correlates positively with *nutrient recovery* via the increased production of vegetables. The criteria mentioned by the other decision aids (Hellström et al., 2000; PHSSDA, 2007) are deemed to be sufficiently covered by the criteria given by Zurbruegg and Tilley (2007).

Selected health-related criteria
On the basis of the considerations presented above the following health-related criteria are applied in the criterion set proposed in this thesis under the heading of the sub-objective *avoiding exposure* (table 4.9, criteria 8-11).

- Prevention of exposure of users
- Prevention of exposure of waste workers
- Prevention of exposure during reuse
- Prevention of exposure of downstream population

These indicators belonging to these criteria are detailed in section 4.5.

4.3.4 Environment-related criteria
An overview of environment-related criteria from the five surveyed decision support systems is presented in table 4.5.

Table 4.5 Environment-related criteria for sanitation systems.

Reference	Environment-related criteria
(Zurbruegg and Tilley, 2007); 1	13 technology-specific criteria: Low use of natural resources *Land* *Energy* *Local construction materials* *Water* Low emissions and impact to the environment *Surface water* *Groundwater* *Soil* *Air* *Noise, smell, aesthetics* High potential for recovery of resources *Nutrients* *Energy* *Organic matter* *Water*
(PHSSDA, 2007, p 29)	1 technology specific criterion: *Small footprint*
(Van der Vleuten-Balkema, 2003, p 24)	6 technology-specific criteria: Low use of natural resources *Land* *Energy* *Nutrients* *Water use and reuse* Low emissions and impact to the environment *Combined sewer overflows* *Discharges of treated water*
(Hellström et al., 2000)	8 technology-specific criteria: Low use of natural resources *Land* *Energy and fossil fuels* *Total exergy* *Water* *High potential for recycling of phosphorus* Low emissions and impact to the environment *Surface water (eutrophication, acidification, toxicity)* *Soil* *Air (global warming)*
(Loetscher, 1999)	1 technology-specific criterion: Low use of natural resources

The decision support tools PHSSDA and SANEX© do hardly specify environmental criteria. The criteria sets of NETSSAF (Zurbruegg and Tilley, 2007), Hellström and co-workers and Van der Vleuten-Balkema are to a high degree similar and both include criteria in the field of low emissions, low use of natural resources and high potential for recovery of resources. Hellström and co-workers limit recovery of resources to recycling of phosphate and arrange this criterion under low use of natural resources.

Discussion

The group of criteria concerning *prevention of emissions to surface water, groundwater, soil and air* discriminates between e.g. pit latrines with their high impact on groundwater and the closed anaerobic-digestion toilet. In this thesis this set of criteria is included in the selection, though '*pollution prevention to soil*' and '*to groundwater*' are grouped into one criterion and the criterion of *prevention of emissions to air* encompasses two sub-criteria: *low methane emissions* and *low odours and insect nuisance*. *Low noise hindrance* is not included as it considered of minor importance in drainage and sanitation technologies. Insect *nuisance* is especially associated with open storage basins for combined-sewage and wastewater-treatment technologies like waste stabilization ponds, constructed wetlands and trickling filters. Also *low emissions of nitrous-oxide* could be considered as an environmental criterion. Since the global warming potential by nitrous-oxide emissions from drainage and sanitation systems was considered significantly lower than the impact of methane emissions, this criterion is not included in the list of table 4.9.

In NETSSAF (Zurbruegg and Tilley, 2007) (table 4.5) the criterion *low use of natural resources* discriminates especially between conventional gravity sewerage and simplified sewerage, but most other technologies have a rather similar overall use of resources. The *use of resources* of a drainage and sanitation system option, including land use, is coming to expression also in the financial criterion of *low life cycle costs*, so that including this group of criteria leads to a certain extent of double counting. Since it may be assumed, however, that the actual market prices of resources do not fully reflect their real value, in particular their uncertain future value, mere financial accounting of avoided resources costs is considered an inadequate way of expressing the value of avoided resource consumption. Consequently, *resources saving* with respect to water, energy and nutrients is included in the list of criteria. *Low land use* is not included as a criterion, as the land use of drainage and sanitation is assumed to be sufficiently accounted for in the calculation of costs.

For criteria related to *recovery of resources* (Zurbruegg and Tilley, 2007) the same argument can be used as for *low use of natural resources*: effective resource recovery would lead to financial benefits, which would reduce *costs* and consequently come to expression under the economic objective. However, for the reason that financial accounting does not completely express the value of recovered resources, resource recovery is designated as one of the environment-related criteria in table 4.9. An additional argument for this criterion could be that the world is now intensively looking for new methods of resource recovery from domestic wastewater and consequently technologies with a high *resource-recovery potential* deserve to be tested and improved. Therefore they have preference over technologies that do not have this potential. *Recovery of organic matter* (Zurbruegg and Tilley, 2007) is not included, as rarely much value is attributed to organic matter from drainage and sanitation systems. There are usually more useful sources of organic matter to improve soils, such as animal dung and source-separated domestic biowaste. The criteria related to *saving* and *recovery* of resources are grouped under one sub-objective (table 4.9).

Selected environment-related criteria
The following environmental criteria proposed in the reviewed literature are applied in the criterion set of this thesis. Under the heading of the sub-objective of p*revention of emissions to water* two criteria are proposed (table 4.9, criteria 12 and 13):

- Low COD emission due to combined sewer overflows and untreated stormwater
- Low N and P emission due to combined sewer overflows and untreated stormwater

Under the heading of the sub-objective of *prevention of emissions to air* two criteria are formulated (table 4.9, criteria 14 and 15):

- Low methane emission
- Low malodours and insect nuisance

Under the heading of the sub-objective of *prevention of emissions to soil and groundwater* one criterion is suggested (number 16):

- Low emission to soil and groundwater

Under the sub-objective of *saving and recovery of resources* three criteria are formulated (table 4.9, criteria 17, 18 and 19):

- Low net consumption of water
- Low net consumption of energy
- Recovery of nutrients

The indicators belonging to these criteria are described in section 4.5.

4.3.5 Social and cultural criteria
Table 4.6 summarizes the social and cultural criteria mentioned in the five reviewed decision support publications related to drainage and sanitation. Apparently, what the different authors call *social and cultural criteria* differs much with respect to phrasing and the degree of technology- or site-specificity. The NETSSAF aid in its totality and most indicators listed by Van der Vleuten-Balkema are technology-specific: they are meant to give a qualification for technology comparison irrespective of the situation under study. The criteria formulated by Loetscher are all site-specific. A further distinction can be made between provider-oriented and end-user oriented social and cultural criteria. Here, the selection of technology-specific criteria focuses on the NETTSAF aid (2007) and the thesis of Van der Vleuten-Balkema (2003).

Discussion
Both NETTSAF and Van der Vleuten-Balkema have a user-oriented criterion that considers *convenience* (namely *high convenience and high level of privacy* (NETSSAF) and *convenience and correspondence with local ethics* (Van der Vleuten-Balkema, 2003). *High*

convenience could discriminate between technologies with and without manual handling of excreta, since handling of excreta in various stages of the sanitation chain is considered inconvenient to both users and waste workers. The addition of the sub-phrase '*and correspondence with local ethics'* among the criteria of Van der Vleuten-Balkema refers to site-specific culture-related opinions of the users and is therefore deemed inappropriate for a technology-specific criterion. In line with the above publications *high convenience* has been chosen as one of the user-oriented criteria. The criterion c*onsideration to issues of women, children and elderly* from NETSSAF seems to hardly discriminate between sanitation technologies and therefore not very relevant. Nevertheless, it is included in table 4.9, since it stimulates stakeholders to not overlook the interests of important end-user categories. Also the group of the *disabled* is added to this criterion. The two criteria *high convenience* and c*onsideration to issues of women, children, elderly and disabled* are selected as user-oriented criteria under the heading of the sub-objective *high convenience to end users* (table 4.9).

Van der Vleuten-Balkema's criterion *stimulation of sustainable behaviour* may be considered as a valuable characteristic of a drainage and sanitation system. However, this criterion has not been added to the list of table 4.9, as fulfilment of this criterion would become apparent in the scores of other criteria like *prevention of emissions*, *resource recovery* and *cost-effectiveness* as well. Accordingly, addition of this criterion could lead to double counting. Stakeholders in the assessment process might however put special worth to this criterion, so that it is added to the site-specific criteria in table 4.10.

Van der Vleuten-Balkema's two provider-oriented criteria *low level of expertise required in design, construction and repair and efforts needed to[…] enforce existing regulations and of embedding of technology in policy making* could discriminate between system options that are easy to manage and therefore appropriate, and those that require more expertise and are more difficult to embed in local policies. These two criteria correspond to some extent with the NETSSAF criterion of *low level of awareness and information required to assure success of a technology*. The fulfilment of this criterion is associated with technology options that require little knowledge of involved actors, like flush toilets, septic tanks and waste stabilization ponds, while urine-diverting toilets and UASB-reactors obtain a low score for this criterion in the NETSSAF aid. The required management capacity of providers is assessed with this criterion. Technologies that comply well with this criterion are easy to implement, since the provider does not have to accompany the hardware implementation with capacity building of stakeholders, including his own staff. In the criteria set of this thesis (table 4.9) the main provider-oriented social and cultural criterion has been formulated as *low requirements to management capacity of providers*.

NETSSAF and Van der Vleuten-Balkema both have a criterion oriented to the participation of end-users in the implementation and operation of technological systems, respectively: *low participation and little involvement by the users* (NETSSAF) and *potential for end-user participation* (Van der Vleuten-Balkema). The criterion *participation and involvement of users* discriminates between technologies for which providers have to seek involvement and build capacity among other stakeholders and technologies where this is not the case. Notably, Van der Vleuten-Balkema judges the *potential for end-user participation* a positive characteristic of a technological system, while in contrast the NETSSAF aid considers the need of *participation and involvement of users* as a liability, and therefore as negative. In several publications *participation and involvement of users* are not only seen as a key to project success, but also as a value by its own right, since user participation in drainage and sanitation could be a basis for participation in other community activities and thus enhance the coherence of the community (Hasan, 1997; Hasan, 2002).

Table 4.6 Social and cultural criteria for sanitation systems.

Reference	Social and cultural criteria
(Zurbruegg and Tilley, 2007)	4 technology-specific criteria: *High convenience and high level of privacy* *Special consideration to issues of women, children and elderly* *Low level of awareness and information required to assure success of technology* *Low participation and little involvement by the users*
(PHSSDA, 2007, p 29)	None
(Van der Vleuten-Balkema, 2003, p 24)	3 technology- and 2 site-specific criteria: *Potential for end-user participation* *Convenience and correspondence with local ethics* *Low level of expertise required in design, construction and repair* *Efforts needed to[…]enforce existing regulations and of embedding of technology in policy making* *Stimulation of sustainable behaviour*
(Hellström et al., 2000)	1 technology-specific, 1 mixed and 2 site-specific: *Easy to understand* *Work demand* *Acceptance* *Availability*[15]
(Loetscher, 1999)	6 site-specific criteria: *Adequate project facilitation* *Strong community involvement* *Strong willingness to participate* *Coordination among agencies* *Compliance with community needs (resource recovery)* *Management ability of authorities*

In the phrasing of the NETSSAF aid the negative judgment about end-user participation seems to be based on the assumption that technologies that can be worked by providers alone are always easier to manage than technologies which require involvement of other actors and cooperation through the chain (users, waste collectors, farmers). The question is if this assumption is shared by the stakeholders in a practical intervention area. This thesis does not include a criterion related to end-user participation, but sees the need of multi-stakeholder cooperation in system management, for example in effluent or sludge reuse schemes, as a complication to a technological system. Consequently, in the criteria set of this thesis (table 4.9) the criterion of *low requirements to institutional support and cooperation through the*

[15] This criterion probably refers to the availability of urban water infrastructure to various user categories in the situation under study.

chain has been included. It may be argued that this criterion is not technology but site-specific. In low-income countries such *low requirements to institutional support* are usually important to the success of a system, but in high-income countries much less so. Since the criteria list elaborated in this thesis is focusing on low-income countries with often overstressed management agencies, low requirements to these institutions are seen as a positive characteristic of technical systems. The criterion *acceptance* of a technology or system by Hellström and co-workers (2000) and the criteria proposed by Loetscher (1999) are all site-specific. They are rather factors that contribute to the success of an intervention, if fulfilled, than criteria to assess a technology. These are criteria with which stakeholders check whether local conditions are suitable to project implementation. They could all be grouped under the site-specific criteria related to *acceptance* by providers and end-users.

Selected social and cultural criteria

Social manageability has been proposed as the main social and cultural objective for drainage and sanitation systems. Under this objective one provider and one user-oriented sub-objective has been selected, namely *low requirements to management capacity of providers* and *high convenience to end-users*. The two technology-specific criteria adopted in this thesis under the provider-oriented sub-objective are (table 4.9, criteria 20 and 21):

- Low requirement of institutional support and cooperation through the chain
- Low requirements with respect to end-user awareness

The selected user-oriented technology-specific criteria are (table 4.9, criteria 22 and 23):

- High user convenience
- Consideration to issues of women, children, elderly and disabled.

The indicators belonging to these criteria are detailed in section 4.5.

4.3.6 Economic and financial criteria

Decision aids should include cost-related criteria, as costs always play an important role in system choice. These criteria are often indicated as ‘economic’ and in this thesis as *economy-related*. What is usually assessed, however, are the *costs* of system options, i.e. financial impact, rather than the impact on the economy which has a wider scope. The difference between an economic and financial assessment is discussed below (4.5). An overview of the economy-related criteria in the five reviewed decision support systems are shown in table 4.7.

Discussion

All five decision support systems have *low capital* and *operation and maintenance costs* in their criteria list and they are also applied in this thesis. These capital and operation and maintenance costs aggregated over the life time of a drainage and sanitation system are indicated as life cycle costs. Accordingly the criterion is worded as *low life cycle costs*. Both NETSSAF and PHSSDA have *benefits from reuse* as an additional criterion. These benefits discriminate between e.g. a septic tank (few benefits) and an anaerobic digester (many benefits: biogas, nutrient-rich stabilized sludge). These benefits could be measured in monetary and non-monetary terms. Monetary benefits could be subtracted from the gross operational costs and lead to a lower figure for the net operational costs. If *benefits from reuse* are accounted for in the operational costs, they could be omitted from the list, but are invisible to the assessors then. As visibility is thought important, the criterion of *benefits from reuse* expressed in monetary terms is adopted as a criterion in this thesis.

Table 4.7 Financial and economic criteria for sanitation systems.

Reference	Economy-related criteria
(Zurbruegg and Tilley, 2007)	4 mixed criteria: *Low construction costs per household* *Benefits to local economy* *Low operation and maintenance costs* *Benefits or income from reuse*
(PHSSDA, 2007, p 29)	2 mixed criteria: *Low capital cost* *Low operation and maintenance costs* *Usability of byproducts*
(Van der Vleuten-Balkema, 2003, p 24)	1 mixed criterion: *Investment and operation and maintenance costs*
(Hellström et al., 2000)	2 mixed criteria: *Low capital cost* *Low operation and maintenance cost*
(Loetscher, 1999)	2 mixed criteria: *Low life cycle costs* *Strong willingness to pay*

It would be correct to take non-monetary (hidden) benefits into account, e.g. for the aspect of soil improvement due to the use of compost made from faecal sludge. The same holds for hidden costs. As non-monetary costs and benefits are difficult to measure and are probably not decisive in technology selection, they are left out of consideration here. The NETSSAF aid also has the criterion: *benefits to the local economy (business opportunities, local employment)*. This criterion gives high scores to reuse activities and low scores to disposal into soil and water. This criterion has been omitted in this thesis as it correlates closely with the criterion *benefits from reuse*, so that it is considered redundant.
Loetscher has *strong willingness-to-pay* as a criterion. This is an entirely site-specific criterion which is another way to judge *user acceptance*. Accordingly, *strong willingness-to-pay* is deemed unsuitable as a technology-specific criterion in table 4.9.

Selected financial and economic criteria
On the basis of the above review of the literature the following economy-related criteria are applied in this thesis under the heading of the objective of *economic desirability* (table 4.9, criteria 24 and 25):

- Low life cycle costs
- High benefits from reuse

These two are the financial criteria providers apply in their system assessment and are related to the costs and benefits to the local economy. They can be considered technology-specific,

though site-specific factors obviously will influence costs and benefits and are detailed in section 4.5.
End-users and other stakeholders in a participatory selection process will be interested in the financial costs and benefits to themselves, which do not correspond automatically with the costs and benefits to the economy as a whole. For households these can be expressed in the site-specific criteria:

- Low cost to the household
- High benefits to the household from reuse

These criteria are included in the list of site-specific criteria (table 4.10).

4.4 Criteria proposed for the SANCHIS method

The criteria to be used for assessment of drainage and sanitation options can be subdivided into three sets (chapter 3, subsection 3.3.4). The first set is the screening criteria which distinguish between feasible and unfeasible system options in the situation under study. As has been argued, screening is carried using the criteria *compatibility with local infrastructure and physical conditions* and *compliance with the local policy framework* (table 4.8). The fulfillment of these criteria is determined by physical, infrastructure-related and policy-related factors reigning in the situation under study. The second and third set are respectively the technology- and site-specific criteria for a comparative assessment of system options. These three sets as proposed here for drainage and sanitation system assessment are presented in tables 4.8, 4.9 and 4.10. The third group are site-specific criteria grouped under the general objective of *stakeholder acceptance.* Stakeholders involved in a drainage and sanitation system selection procedure may compose a set according to what they find important in their situation.

Table 4.8 Screening criteria and restrictive site-specific factors selected in SANCHIS.

Objective	Criteria	Restrictive site-specific factors (screening)	Nr
Technical functionality	Compatibility with local infrastructure and physical conditions	Climate, rainfall, soil conditions, housing density, water consumption, topography	1
	Compliance with the local policy framework	Local policies and regulations	2

Table 4.9 Main objectives, sub-objectives and technology-specific criteria selected in SANCHIS for comparison of drainage and sanitation systems.

Objectives	Sub-objectives	Criteria	Nr
Technical functionality	Reliability	Low level of skills needed in construction	3
		Low level of skills needed in operation	4
		Low sensitivity to irregular maintenance	5
		Independence of external supplies (e.g. power, chemicals) and services	6
	Flexibility	Ease of adaptation to new conditions and requirements	7
Protection of health	Avoiding exposure	Prevention of exposure of users	8
		Prevention of exposure of waste workers	9
		Prevention of exposure during reuse	10
		Prevention of exposure of downstream population	11
Environmental protection and material resources conservation	Prevention of emissions to water	Low COD emission due to combined sewer overflows and untreated stormwater runoff	12
		Low N and P emission due to combined sewer overflows and untreated stormwater	13
	Prevention of emissions to air	Low methane emission	14
		Low malodors and insects nuisance	15
	Prevention of emissions to soil and groundwater	Low emission to soil and groundwater	16
	Saving and recovery of resources	Low net consumption of water	17
		Low net consumption of energy	18
		Recovery of nutrients	19
Social manageability	Low requirements to management capacity of providers	Low requirements to institutional support and cooperation through the chain	20
		Low requirements with respect to end-user awareness	21
	High user convenience	High convenience	22
		Consideration to issues of women, children, elderly and disabled	23
Economic desirability	Cost-effectiveness	Low life cycle costs	24
		High life cycle benefits from reuse	25

The set of table 4.10 is an example. In a SANCHIS decision-making process stakeholders jointly compose a list of possible system options and carry out the screening of options making use of the criteria of table 4.8. The comparison of options with the technology-specific criteria of table 4.9 is primarily carried out by experts who inform other stakeholders about the results. Finally, the assessment with respect to site-specific criteria (table 4.10) mainly involves end-users and providers.

Table 4.10 Main objective, sub-objectives and site-specific criteria for comparison of drainage and sanitation systems (an example for end-users).

Objective	Sub-objectives	Criteria
Stakeholder acceptance (end-users)	Technical functionality	High level of technical performance
	Protection of health	High level of health protection
	Environmental protection and resource conservation	High level of environmental performance
	Social and cultural acceptance	Willingness to invest (banks and government)
		Support by provider(s)
		User convenience
		Safety
		Cultural acceptability
		Stimulation of sustainable behavior
	Financial affordability	Low life cycle costs to the household
		High life cycle benefits to the household from reuse

4.5 Indicators

As pointed out in chapter 3 indicators are parameters with which criteria fulfillment is measured in a quantitative or qualitative way. This measurement leads to qualitative judgment or a quantitative performance score. In this section 4.5 the subsections 4.5.1 until 4.5.5. discuss the indicators for measurement of the degree of fulfillment of the criteria listed in table 4.8 and 4. 9. The set of criteria in table 4.10 is meant as an example of site-specific criteria produced in a meeting of end-users. Providers could compose their own and a different set. The use and meaning of sets of criteria proposed by stakeholder groups is discussed in subsection 4.5.6.

4.5.1 Technical functionality

The screening that distinguishes between feasible and non-feasible system options is carried out with the criteria *compatibility with local infrastructure and physical conditions* (1) and *compatibility with local policy framework* (2) (table 4.8). In chapter 6 screening aids based on the restrictive factors indicated in the third column of table 4.8 are introduced that can be used to determine the applicability of technologies and technology chains. After having applied screening to eliminate unfeasible system options from the options comparison, the remaining feasible options are compared using the criteria of table 4.9.

Under the main objective of *technical functionality* there are two sub-objectives *reliability* and *flexibility*. These sub-objectives are judged through five criteria (3-7) and their related indicators.

Here, the *level of skills needed in construction* is the indicator used in the assessment of fulfillment of the criterion *low level of skills needed in construction.* The *level of skills needed in construction* (3) is measured in a qualitative way. The performance score depends on the type of technology applied. The score is high (positive judgment) if construction can be carried out by individual households with the help of local craftspeople on the basis of a simple standard design, and low (negative judgment), if the construction requires an individual design and complex skills and machinery for construction. The latter is the case for mechanized wastewater-treatment plants. A low *level of skills for construction* means that a technology can be implemented in a simple way, even under a regime of self-help. Sanitation-system scale also has consequences to the skills needed: small local sewer systems need less skills than large-scale sewer systems.

For the *level of skills needed in operation* (4) the same qualitative way of measurement is applied as for the previous criterion. It is assumed that a *low level of needed skills* has a positive effect on the reliability of a technology or chain of technologies, as low skills imply a more prompt repair and less chance of lasting failure.

The criterion *low sensitivity to irregular maintenance* (5) is important to reliability. Irregular maintenance is common in developing countries, especially in the field of drainage and sanitation. The *sensitivity to irregular maintenance* is estimated in a qualitative way. Technologies and systems that need regular maintenance, such as sewers with a high risk of clogging due to transport of solids and mechanized wastewater-treatment plants, are attributed a low score on this criterion. Systems that could withstand a certain period on negligence, such as septic tanks, Imhoff tanks and waste stabilization ponds are deemed relatively insensitive and receive a higher performance score.

Reliability could be positively affected by *independence on external supplies and services* (6), especially in situations where these supplies and services are not always available. The attribution of a performance score to *independence* may include the aggregation of assessments of the supply of energy, chemicals (especially disinfectants), spare parts and maintenance services.

Ease of adaptation to new requirements (7) as an expression of flexibility depends on efforts and expenditures needed adapt a system to a new situation. Adaptation of large systems with high investments in networks and equipment, long decision procedures and many stakeholders is more difficult and expensive than adaptation of stand-alone small systems. On-site and community-scale are more adaptive than large-scale transport, treatment and reuse systems. Flexibility could be expressed in the estimated costs of several ways of upgrading.

4.5.2 Protection of health

Though drainage and sanitation systems are designed to *avoid exposure* (8-11) to pathogenic organisms (and hazardous chemicals) and protect public health, not all technologies are equally adequate in this respect. The lack of adequateness is measured in a qualitative way as *risk of exposure*, where a distinction is made between users of toilets (end-users), waste workers, people who work with reusable products (recoverers) and downstream population who may inadvertently be exposed to pathogens (or toxic chemicals) present in wastewater and faecal sludges. Technologies that imply manual work (pit and tank emptying) with black water and faecal sludges have a relatively high risk of exposure, and therefore a low score, for this criterion, as waste workers may come in direct contact with infective material. A high frequency of combined sewer overflows may cause health risks to the downstream population of a wastewater-treatment plant, even where such a plant is provided with effluent disinfection. Quantitative Microbial Risk Assessment is a method to estimate the risks of exposure (WHO, 1999; Höglund, 2001, p 26).

4.5.3 Environmental protection and material resources conservation

While all feasible systems under study should comply with legal emission requirements, some of them could be preferable by virtue a surplus prevention of emissions leading to *low COD emissions* (12) and *low nitrogen and phosphorous emissions* (13) via reduced loads to wastewater-treatment plants, reduced combined-sewer overflows and treatment of stormwater runoff. Particularly systems with source-separation of urine, faeces, grey water and stormwater are capable of a high degree of surplus emission prevention.

Drainage and sanitation systems often emit to the atmosphere: *methane* (14), *malodors and insects nuisance* (15) and to *soil and groundwater* (16) (e.g. improperly constructed septic tanks, soakage pits and leaking sewer lines). High emissions of the potent greenhouse gas methane are associated with anaerobic treatment technologies where the produced methane is not captured, such as septic tanks. Emissions of carbondioxide (CO_2) are evaluated here under the criterion 18 of *low net consumption of energy*. Other emissions of secondary importance, which are not assessed here, are ammonia (NH_3) and nitrousoxide (N_2O).
Environmental infrastructure preferably should lead to *saving and recovery of resources* which would result in a *low net consumption of water* (17) for domestic and industrial purposes and in irrigation, *low net consumption of energy* (18) and *recovery of nutrients* (19). Low net consumption is the aggregated value of resources saving and recovery. In a studied situation a mere potential of resource recovery does not lead to a positive assessment; only realized recovery should be rated positively. If recovered products can be sold or avoid costs in running the drainage and sanitation system, the positive effect of resource recovery comes to expression in reduced costs of the system as well. As explained above in section 4.3.4 this double counting is accepted as also non-monetary advantages of resource recovery are valued.

Low net consumption of water (17) is made possible through water saving and water reuse. Water saving is enhanced through the use of water saving equipment in the households. Water reuse requires adequate treatment of sewage, black water, or grey water. Systems with source-separation of black and grey water deliver a grey water effluent with a relatively low concentration of salts, which yields more flexibility to farmers than irrigation with treated sewage. Consequently, systems with black water source separation are preferred to systems which collect sewage. This criterion can be evaluated by means of the net water consumption (gross consumption – reuse), expressed in volume per household per unit of time.

The criterion *low net consumption of energy* (18) assesses the gross energy consumption minus the energy recovery of the compared system options expressed in MJ primary energy per person (or per household) per unit of time (MJpe/cap.yr). A low consumption and high production lead to a high performance score on this criterion. The net energy consumption of a drainage and sanitation system as a whole is the sum of the net energy consumptions of the technologies that constitute the system, including the energy used for the production and transport of flush water for toilets, transport and treatment of wastewater and sludge, and energy associated with the reuse of products from wastewater.
Energy recovery could result from the utilization of biogas generated by anaerobic treatment and digestion facilities, either on-site or off-site. In addition, energy recovery in the form of avoided energy consumption associated with the reuse of products from wastewater, such as nutrients in irrigation water, is included in the calculation of the net energy consumption.

The *recovery of nutrients* (19) of system options under study is measured as the nutrients nitrogen and phosphorous that are recovered and reutilized as fraction of the nutrients that enter the system. Nutrients can be reutilized as part of biosolids, of effluent and special products like struvite.
The value of the indicator F_{nut} according to equation 4.1 may be used to express the degree of criterion fulfillment:

$$F_{nut} = \frac{\frac{N_{reut}}{N_{in}} + f_P * \frac{P_{reut}}{P_{in}}}{1 + f_P} \qquad (4.1)$$

Where:
F_{nut} = nutrient reutilization value (0 – 1);
N_{reut} and P_{reut} = reutilized loads of nitrogen and phosphorus (tonne/yr);
N_{in} and P_{in} = input nitrogen and phosphorus loads (tonne/yr);
f_P = factor expressing the relative importance of P as compared to N recovery (f_P = 1, if both recoveries are equally important).

The assessor determines the value of f_P on the basis of policy priorities concerning nutrient recovery. The approach suggested with the use equation (4.1) presupposes that the generated loads of nutrients can be meaningfully utilized. If this is not the case, e.g. because the recovered loads are insignificant, the value of F_{nut} is zero and nutrient recovery must be neglected.

4.5.4 Social manageability
Social manageability encompasses the four criteria: low requirements to institutional support and cooperation through the chain (20), low requirement to end-user awareness, high convenience (21) and considerations to issues of women, children, elderly and disabled (22).

Institutional support and cooperation through the chain (20) is considered a prerequisite for system sustainability. The performance score for this criterion depends on the number and importance of institutions (governmental agencies, public services companies) required to make the technological system work. Off-site systems and systems with reuse of end-products need more institutional support and cooperation through the chain than simple on-site systems where effluent is discharged to the subsoil. Technologies and systems that need less support and cooperation are deemed more manageable than systems that much support.

Low requirements with respect to end-users awareness (21) are desirable from the point of view of providers as systems that require a permanent effort of awareness raising are deemed less manageable than systems that do not need such an effort. Awareness could be needed if stakeholders (end-users, waste workers and others) have to regard special rules and require knowledge to make a technology or system work. An examples is the awareness to avoid the discharge of toxic substances in reuse-oriented systems.

High convenience (22) refers to end-users' assessment of the convenience of toilets and on-site treatment technologies. Convenience can be reduced where an (unusual) not enjoyable effort is required, such as cleaning and handling of excreta.

The criterion *consideration to issues of women, children, elderly and disabled* (23) is related to the wishes of the mentioned groups concerning the safety and user-friendliness of toilet systems.

4.5.5 Economic desirability

The objective of *economic desirability* of a drainage and sanitation investment expresses the wish that improved infrastructure be a useful and attractive investment in the situation under study. Economic desirability of projects is typically assessed by means of benefit-cost analysis (Kalbermatten et al., 1982; Nas, 1996; Mishan and Quah, 2007). In fact, benefit-cost analysis is an alternative to multi-criteria decision analysis in making a best choice among various project options (Sugden, 2005). Economic benefit-cost analysis compares the economic effects of an intervention, expressed in monetary terms, with the option of doing nothing and with other interventions. A substantial problem in economic benefit-cost analysis is the difficulty to identify and quantify all relevant benefits and costs. Economic benefits may include money revenues, but also less tangible effects in the domain of improved well-being and health, economic growth, increased employment, saving and recovery of resources and a better environment. In the same way do costs comprise monetary expenses, but also non-monetary costs, such as e.g. lost bio-diversity. Adequate drainage and sanitation is a basic need with a high benefit-cost ratio (Hutton and Haller, 2004), so that in practice economic comparison with other types of investment or the option of doing nothing will rarely be undertaken. Consequently, the economic question becomes which drainage and sanitation option is most cost-effective[16] in the situation under study. The criteria used for *cost-effectiveness* are *low life cycle costs* (24) and *high life cycle benefits from reuse* (25). In fact, in this way the evaluation of the *economic desirability* of various potential investment opportunities has been reduced to a least-cost comparison, a procedure discussed by

[16] Cost-effectiveness analysis is a benefit-cost analysis carried out under the assumption that the benefits for all evaluated system options are equal, i.e. all evaluated options reach an aspired service level.

Kalbermatten and co-workers (1982, p 50). Chapter 7 of this thesis presents a data base of the operational costs and financial revenues from reuse of products from wastewater referring to the drainage and sanitation system options introduced in chapter 5 and 6. The life cycle costs and benefits are measured in an approximative way by means of the indicators Total Annual Costs per Household (TACH) and Total Annual Benefits per Household (TABH), thereby assuming that all system costs have to be borne by the beneficiaries of the system, i.e. the households. No attempt is made to add monetized indirect and intangible costs and benefits of drainage and sanitation systems to the direct and tangible financial costs and benefits. This approach seems in this case legitimate for two reasons. First, the intended comparison of costs and benefits of system options takes place independent from concrete situations, so that financial expression of external effects would be speculative or even irrelevant. Second, drainage and sanitation systems aim at reduction of negative health and environmental impacts, so that it may be assumed that the external benefits of the compared systems are equal, and the possible external costs are much smaller than the direct financial costs. Therefore, the proposed financial evaluation used in chapter 7 renders a good first approximation of the involved costs and benefits.

4.5.6 Site-specific criteria proposed by stakeholders

In subsections 4.5.1 – 4.5.5 the screening between feasible and unfeasible drainage and sanitation system options and the comparison of feasible options on the basis of the technology-specific criteria are discussed. The screening requires insight in the *compatibility* of system options with the situation under study and therefore participation of end-users, technical specialists and managers. Comparison with technology-specific criteria can be carried out irrespective of the area under study and requires technological expertise. These two stages of the systems selection may deliver a set of presumably most appropriate options for the area under study. Before politicians take the final decision, they will want to be informed about opinions about the selected options among stakeholders: end-users, provider agencies, involved workers, users of reusable products.

For this third stage each of the relevant stakeholder groups or representatives may propose its own set of criteria. An example of a set of end-user criteria is shown in table 4.10. It is at this stage that the institutional and socio-cultural factors that influence the performance of the infrastructure are assessed. Stakeholders are informed about the results of the preceding stages, i.e. options' performance with respect to technical, health, environmental and cost aspects, and subsequently bring in their own expertise with respect to factors that affect options performance. These stakeholder inputs may concern all criteria the specialists have assessed, but especially the issue of *acceptance*. End-user acceptance for example may be determined by site-specific factors like the degree of *convenience and privacy* offered by toilet options, the *consideration to issues of women, children, elderly and disabled, safety* and *cultural acceptability*, *support by providers* (do they help me if things go wrong?) and the *financial affordability* (what do households have to pay and are they able to pay it?). The institutional, and socio-cultural criteria are assessed by qualitative and the financial criteria by means of quantitative judgment (e.g. USD/hh.yr).

Through an evaluation of site- (stakeholder-) specific criteria the decision makers will obtain information about the affordability of the options, the willingness-to-pay of the end-users, willingness-to-participate in maintenance activities, the capabilities of providers to sustain proposed systems, etc. If stakeholders' opinions about options would differ much, study could be done about how objections against certain options could be mitigated and more consensus be reached.

4.6 Summary

In this chapter the objectives, criteria and indicators are proposed for decision making about drainage and sanitation system options. After the stakeholders in the decision-making process have composed a long list of conceivable system options, the assessment of these options consists of three stages: screening, comparison with respect to technology-specific criteria and comparison with respect to site-specific criteria. It is proposed that all relevant stakeholders and not only technical specialists participate in the first stage of screening as detailed local knowledge is required. In this stage stakeholders or their representatives should judge if options could work under the physical, infrastructure and legislative conditions of the intervention area. The second stage of comparison is mainly a task of specialists. For the comparison of options with regard to technology-specific criteria specialists should dispose of sufficient information about the strengths and weaknesses of the system options under study. For this comparison of options the SANCHIS method proposed a list of 23 criteria. Finally, all stakeholders or their representatives participate in the third stage of options' assessment in which the focus is on acceptance of proposed systems. The criteria in this stage are site-specific and differ with the stakeholder groups. By way of an example a set of criteria suitable for judgment by end-users is suggested. The application of the criteria sets developed in this chapter is demonstrated in chapters 10 and 11.

CHAPTER 5 DRAINAGE AND SANITATION SYSTEM OPTIONS

5.1 Introduction

Multi-criteria decision analysis was introduced in chapter 3 as a tool for decision-makers to make choices about drainage and sanitation infrastructure that are rational and meet agreement among the stakeholders. An important element in this method is the identification of possible system options and their consequences to solve the problem under study. Accordingly, the research question elaborated on in this chapter is: Which are the drainage and sanitation system options applicable in cities in developing countries? The chapter consists of the following sections. First section 5.2 defines drainage and sanitation as part of the urban water cycle and sets the goal to be reached. In 5.3 the quantities and composition of municipal wastewater are outlined. Subsequently, sections 5.4 and 5.5 identify and classify a wide array of regular and innovative drainage and sanitation system options. Finally, in 5.6 the innovative character of the system options list is highlighted and justified.

5.2 Drainage and sanitation within the urban water cycle

Drainage and sanitation in cities is a part of the urban water cycle. This cycle is conceptualized in figure 5.1. The cycle can be considered as consisting of three main domains: (1) *water supply*, (2) *drainage and sanitation*, and (3) the *water environment*, which includes surface water and groundwater. The cycle is fed by rainwater. The part of the rain water that is collected on paved surfaces (roofs and streets) will become *stormwater runoff* that has to be disposed of via the system of urban drainage. Harvested rain water can be a source of water provision. Surface water and groundwater are the main sources in the production of high-quality drinking water and a possible second-quality water to be used for non-drinking purposes (B-water). Water consumption results in various kinds of wastewater, here indicated as *source streams*. The quantity and composition of the source streams are detailed below in section 5.3.

The drainage and sanitation systems can be considered as built up of six *processes* that consumed water undergoes on its way from the household and public-commercial units to its final destination (reuse/utilization or disposal). These six processes are: (1) water consumption, (2) on-site storage and treatment of wastewater, (3) wastewater collection and transport, (4) off-site wastewater treatment, (5) reuse, and disposal (6) (Zurbruegg and Tilley, 2007; Tilley et al., 2008). Effluent of wastewater-treatment plants can be discharged to surface water or reclaimed directly for various purposes among which irrigation in agriculture and reuse in aquaculture are two of the most obvious.

The treatment of urban wastewater delivers certain streams of *products* which are returned to the environment. In sewage treatment the most important products are purified effluent and sludges. In what are called here *reuse-oriented systems* additional products may result: energy from biogas and fertilizers that contain the phosphorus and nitrogen from sewage. All these products have to comply with quality requirements that determine the nature of the treatment technologies. The treatment technologies need *resources* (capital, skilled labour, equipment, land, energy, chemicals) to reach the required product qualities. It is the challenge in the design of drainage and sanitation systems to obtain optimum product qualities at a minimum of resources depletion.

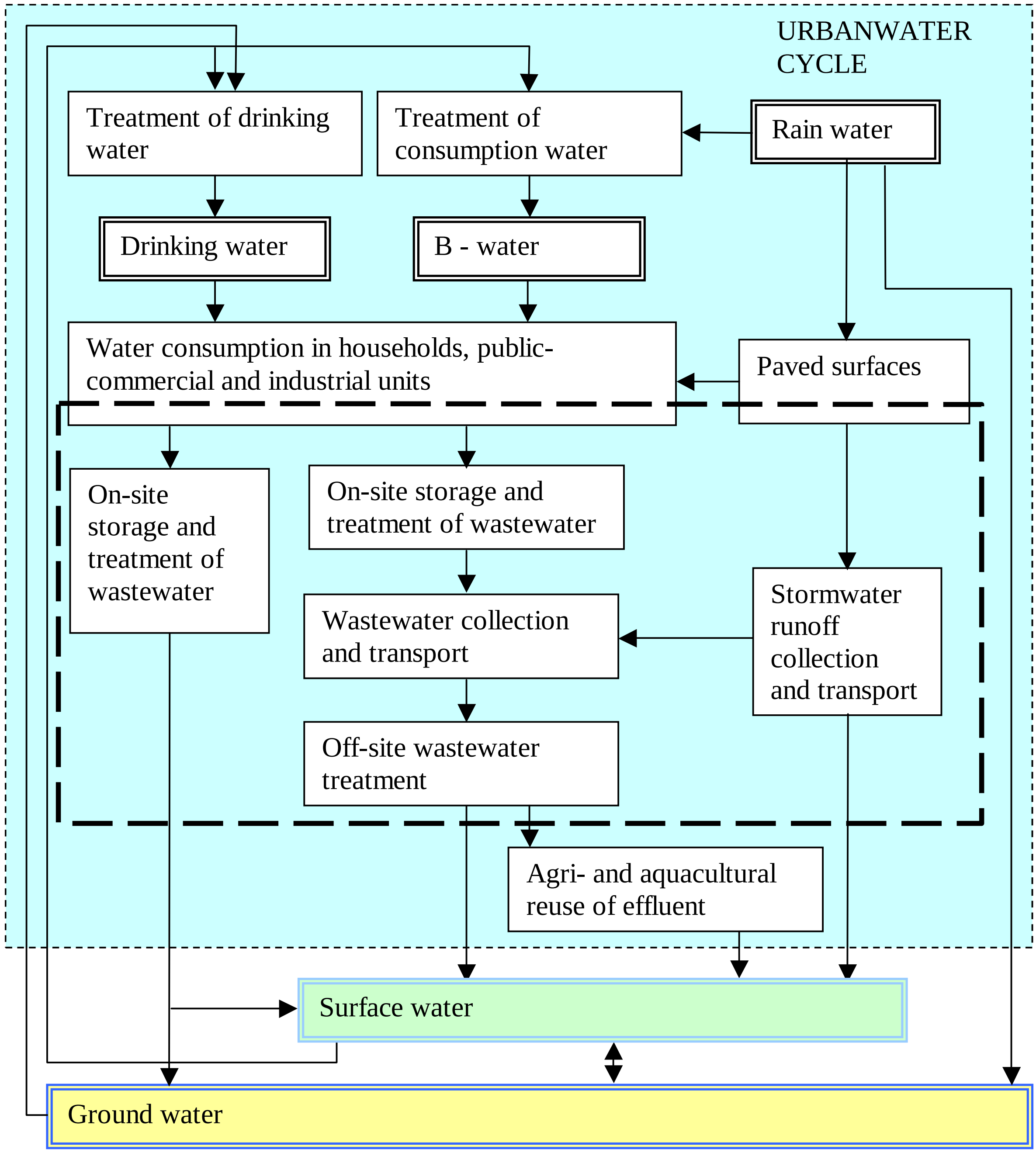


Figure 5.1 The urban water cycle after ONRI werkgroep riolering (2008). The processes inside the bold dotted rectangle belong to the drainage and sanitation system.

5.3 Quantity and composition of municipal wastewater

As several of the drainage and sanitation system options presented in this chapter are based on separation of waste streams at source, first an introduction to these streams is given. The conceptual basis for the analysis of the composition of municipal wastewater is given in Figure 5.2.

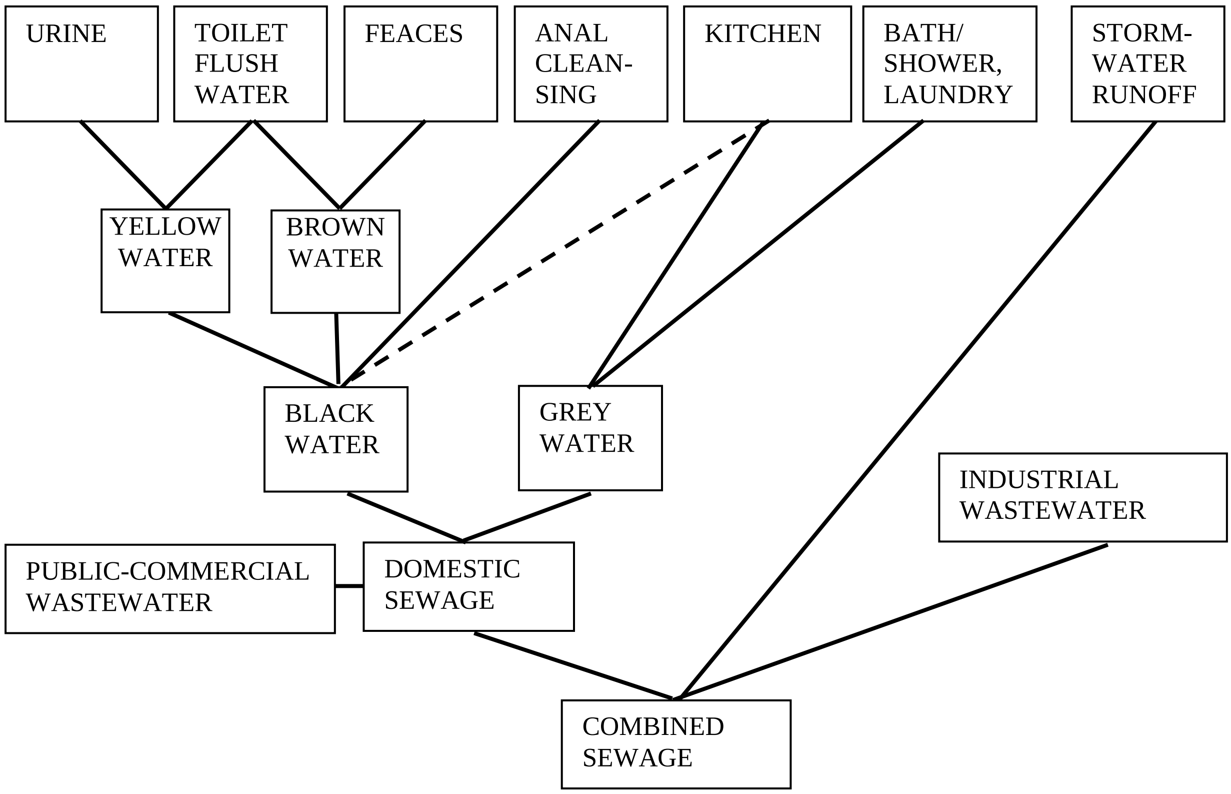


Figure 5.2 Different types of municipal wastewater.

The wastewater in a city comprises wastewaters from households, the public-commercial sector, industry and stormwater runoff. The wastewater from residential areas consist of seven *source streams,* namely urine, toilet flush water, faeces, kitchen wastewater, water used for personal hygiene (anal cleansing water, baths and showers), water used for washing clothes (laundry) and stormwater runoff. Figure 5.2 shows the source streams and various combinations: the *waste streams*. *Yellow* and *brown water* are the combinations of respectively urine and faeces with toilet flushing water. The combination of faeces and urine without addition of flush water is called *excreta* or *nightsoil*. *Black water* is the wastewater from toilets, which conveys urine, faeces, anal cleansing water and flushing water. *Grey water* (also named *sullage*) is the mixed waters from kitchen, bath, shower, laundry-washing and other domestic uses. Due to its high concentration of organic matter, among which oil and fat, kitchen-wastewater could be usefully combined with the black water (the dotted line in figure 5.2). All combined domestic streams form *domestic sewage. Public-commercial wastewater* can be considered as being composed of the same source streams as domestic sewage, though the proportions may differ from domestic wastewater. In cities domestic sewage and public-commercial wastewater are often combined with *industrial effluents* and stormwater to form *combined sewage.*
As it is impossible to generalize about industrial discharges, which may stem from a wide array of industries, in the following text their impact is considered in a qualitative way only. Now first, quantitative and qualitative aspects of the different source streams are discussed.

Domestic wastewater
Indicative values of quantities and the pollution loads of the different source streams of domestic wastewater, i.e. wastewater from residential areas, are presented in tables 5.1 and 5.2. and used as the basis for calculations in this thesis. Though there are differences in pollution loads between households, communities, regions and countries, for ease of survey single values are presented. They represent averages of values found in several studies concerning multiple-tap households. Most of these studies took place in developed countries.

Table 5.1 Indicative quantities of source/waste streams in residential areas (compiled by Kujawa(2005).

Source/waste streams	Quantities (kg/cap.d)
Faeces	0.15
Urine	1.25
Toilet flush water (Cistern flush toilet)	42
Grey water	90
Stormwater	0 – 200

Table 5.2 Indicative loads discharged into residential wastewater (Kujawa, 2005; WHO, 2006).

	COD_{tot} (g/cap.d)	N_{tot} (g/cap.d)	P_{tot} (g/cap.d)	Faecal Coliforms (#/cap.d)
Black water	57	12.5	1.5	10^{10}
Faeces	45	1.5	0.5	10^{10}
Urine	12	11	1	very low
Grey water	52	1	0.5	10^{9}
Total domestic wastewater	109	13.5	2.0	$1.1*10^{10}$

Table 5.2. presents data for the most important macro-parameters COD, N_{tot}, P_{tot}, and faecal coliforms. Important insights from the data given above are: 1) human excreta (faeces and urine) alone contains about 90% of N and 75% of P in only 1-1.5% of the volume of domestic sewage, 2) urine contains about 80% of the N and about 50% of P discharged to domestic wastewater, 3) faeces contributes about half of the load of COD and constitutes a much higher risk in the transmission of human pathogens than urine (WHO, 2006, p 36), 4) grey water contains about half of the organic matter, little nitrogen and phosphorus and a small fraction of the excreted intestinal organisms. The indicated faecal coliform load of grey water of 10^9 corresponds to a concentration of about 10^6/100 ml. Values of this magnitude are recorded in literature though also much lower values were found (WHO, 2006, p 37). Other relevant substances in domestic wastewater are organic micro-contaminants among which hormones and pharmaceutical residues, which are discharged primarily via urine (Ternes and Joss, 2006; Winker et al., 2008).

Stormwater runoff
The flow of stormwater per unit of surface area depends on land use and climate in the municipality under study. Runoff discharges in urban areas are an order of magnitude larger than wastewater discharges. Stormwater runoff can be considerably polluted with soil,

organic matter, metals and mineral oil, due to atmospheric deposition, erosion, wastewater and municipal solid wastes from streets and roofs, particularly after a long period of drought. Pollutant loads of stormwater runoff (kg/event) will mainly depend on the type of land use in the drained area and runoff volume (m^3/event). In a summary of runoff pollution in several places of the world Wiggers and co-workers (1977) show that the average BOD_5 concentration of runoff from residential areas varies between 7 and 36 mg/l, but the maximum values reach 80 mg/l. A study of stormwater runoff from urban residential areas in the US demonstrated event-mean concentrations for COD, N_{tot} and P_{tot} of 70 – 330 mg/l, 0.44 – 8.79 mg/l and 0.05 – 1.84 mg/l respectively (Brezonik and Stadelmann, 2002). Measurements in The Netherlands show indicative pollution concentrations of stormwater runoff of 40 mg/l COD and 2.7 mg/l BOD_5 (RIONED, 2002, p 56). As runoff, especially from areas with extensive commercial activity, should be considered as diluted wastewater, its treatment is recommended.

Food waste
In some reuse-oriented sanitation configurations (table 5.4), where the black water is submitted to anaerobic digestion food waste can be co-treated. The assumed daily amount of this waste is 0.2 kg wet weight/cap.d, with a COD-load of 63 g/cap.d (Kujawa-Roeleveld et al., 2005). Before transport the food waste has to be shredded by means of a grinder in order to enhance the treatment process.

5.4 Classification of drainage and sanitation system options

5.4.1 Principles of the classification
This section proposes a systematic classification of drainage and sanitation system options included in the SANCHIS data-base. As described above urban wastewater consists of seven source streams (figure 5.2) which undergo, separately or in combination, a series of processes (figure 5.1) on their way from the household, or public-commercial unit, to the point of discharge into the environment. The inventory of drainage and sanitation system options, summarized in table 5.3 below, represents the many different ways that these source streams can be handled.
Figure 5.3 explains the symbols used for the systematic display of one specific drainage and sanitation system option. The example is of a system that uses urine-diverting flush toilets. The top part of the figure shows the collection, transport and disposal of *stormwater runoff*. The lower part represents the generation of *urine*, *brown water* and *grey water* in the household, followed by on-site storage and treatment of urine and by septic-tank treatment of brown water plus kitchen wastewater. Effluent of the septic tank and grey water is jointly transported to the off-site wastewater-treatment plant (WWTP). Urine is transported by cartage for utilization. This systematic of in-house installations that combine source streams to waste streams, which subsequently travel through a series of storage, transport and treatment processes leads to 58 drainage and sanitation system options clustered into 12 system groups as summarized in table 5.3. Examples of applications of the mentioned system groups are presented in table 5.4.

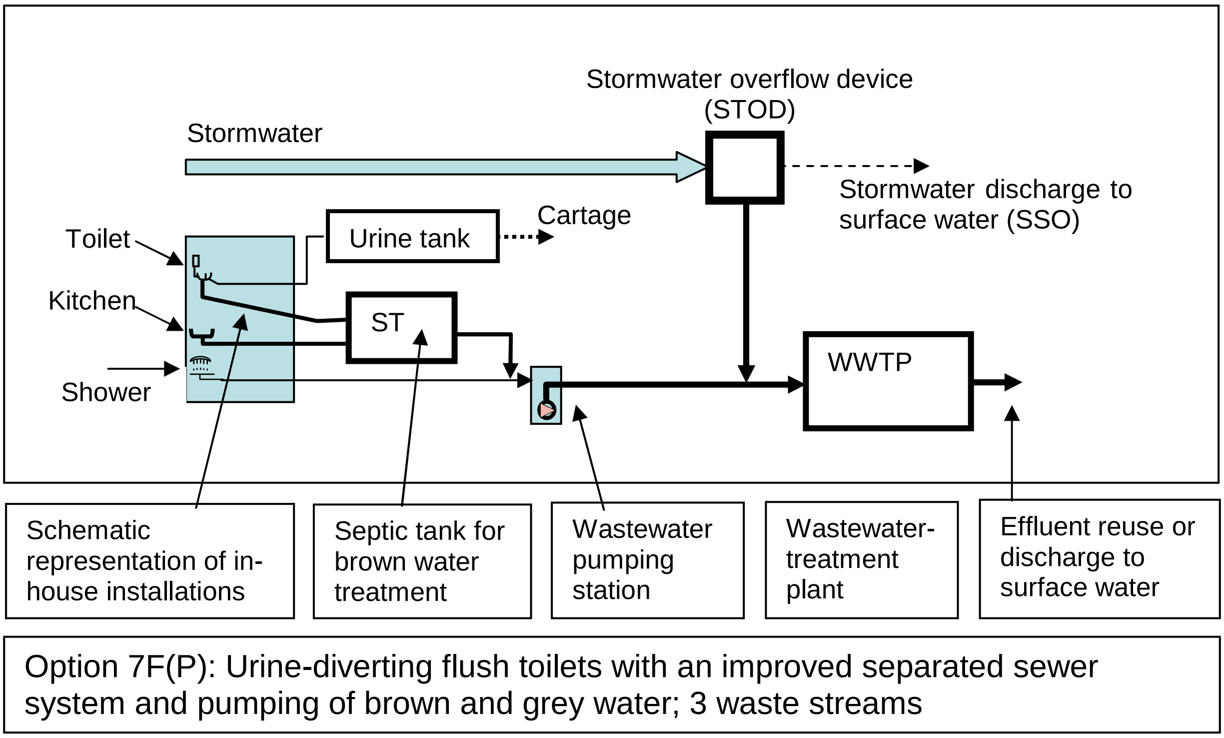


Figure 5.3 Schematic presentation of a drainage and sanitation system option showing source streams, waste streams and processes.

An overview of the system groups and their system options is shown in detail in figures 5.5.1-5.5.12 making use of the principles shown in figure 5.3 above. In order to understand the origin of the different system options, first the factors are described that determine the differences. These factors are named *distinctions*. These distinctions are:

1. Location of treatment: on-site, hybrid or off-site storage and treatment;
2. At-source segregation of source streams: 6 types of toilets are proposed which differ with regard to the combined or separate handling of source streams and which determine the nature of the system to a high degree;
3. The number of piped transport systems, which varies between 1 and 3. Piped system transport a single or combined source streams.
4. Location of toilets: household or communal toilets;
5. Application of enhanced storage capacity of sewer systems: systems differ with respect to the availability of settling-retention basins;
6. On-site removal of solids: systems with or without on-site removal of solids from sewage or black water by means of a septic tank;
7. On-site treatment of grey water in septic tanks: the application of septic tanks with or without co-treatment of grey water;
8. Application of stormwater runoff treatment: systems differ with respect to the presence of a device to send stormwater runoff to the wastewater-treatment plant (so called improved separate sewer systems);
9. Pumping of sewage: systems with and without pumping of sewage.

The meaning of these distinctions to the categorization of system groups and system options in table 5.3 is briefly explained here. An overview of the systematics of the classification of all system options is presented in Appendix 5.1.

Distinction 1: On-site, hybrid and off-site treatment

The nature of sanitation systems depends strongly on local conditions, among which water consumption and the way water is supplied to the household are most important (table 5.3, column 1). While *hand-carried water supply* usually leads to a relatively low water consumption and *on-site* treatment of wastewater (system groups 1, 2), the availability of *piped water supply* commonly results in the use of flush toilets and water-consuming accessories with a high production of grey water (system groups 3 – 12). At a high water consumption the resulting wastewater can be disposed of on-site only where the building density is low (system group 3). At high building density piped water supply is usually associated with *off-site* treatment of wastewater (table 5.3, column 2, system groups 4 - 12). System options with on-site treatment of some source streams and off-site treatment of faecal sludge are called *hybrid* on-site systems. The system groups 4 until 12 are off-site treatment systems with a further distinction between a cluster of *central and community based off-site sanitation groups* (system groups 4 until 7) and strictly *community-based off-site sanitation groups* (system groups 8 until 12) (table 5.3, column 2, 3). The distinction between these two clusters of system groups is explained below.

Distinction 2: At-source segregation of streams

A further sub-division of the system groups is made according to the applied segregation of source streams. The aim of segregation is a higher overall sustainability of the drainage and sanitation system stemming from utilization of end products, reduced emissions and lower use of energy. Segregation of source streams is closely associated with the types of toilets, household appliances and plumbing used. In total 6 toilet types are applied: dry anaerobic digestion toilets, urine-diverting dry toilets with dehydration of faecal matter, urine-diverting flush toilets, vacuum-low flush toilets, pour-flush toilets and cistern-flush toilets. Dry and low-volume flush toilet technologies are used in particular where water is scarce or much importance is given to recovery of biogas and nutrients. Table 5.3 column 4 mentions the toilet types used in each system group and column 5 summarizes the utilizable products of each system group. The different toilet systems are discussed in detail in chapter 6.

Distinction 3: The number of piped transport systems

In *off-site sanitation* systems all generated waste streams have to be transported away from their sources. A further distinction may be made according to the way this transport is carried out: i.e. by *cartage* for dry sanitation methods and through *pipes*. In many water-consuming sanitation systems cartage plays a role as well: e.g. in the removal of sludge from septic tanks and in transport of urine. The number of piped transport systems is correlated with the at-source separation of source streams discussed above. The maximum number of separate waste streams is assumed to be *four*. This maximum number is reached where stormwater, grey water and brown water have their own piped network and urine is transported by cartage (system group 12). For practical reasons the maximum number of separate *piped* networks is assumed to be three. Collection of source-separated urine by pipes (system groups 5, 7, 8, 10, 12) is considered to be limited to a small area or a building, since larger urine networks may suffer from serious clogging. Such a urine collection system is not called a piped network, as it is small. The distinction between the groups 4 – 7 and 8 – 12 is determined by the necessity of local treatment of source-separated concentrated black water and faecal matter. It has been assumed that the off-site systems of groups 8 – 12 with separate transport and treatment of concentrated black water, brown water and faecal matter can be applied at community-scale only. The systems of groups 4 – 7 do not have restrictions with respect to scale.

Distinction 4: Location of toilets
In the on-site system groups 1 until 3 the distinction is made between options with household and communal toilet facilities. Communal toilet blocks are particularly appropriate where there is no space for toilets in or near the household.

Distinction 5: Application of enhanced storage capacity of sewer systems
The principal feature of combined sewer systems is the joint transport of stormwater and domestic wastewater. At high rainfall intensities the conveyed flow exceeds the capacity of the wastewater-treatment plant, so that a part of the combined sewage has to be discharged without treatment as combined-sewer overflow (CSO). The installation of retention basins that provide enhanced storage capacity is a way to reduce the frequency and pollution load of these CSOs. A distinction is made between system options without and with such combined sewage retention basins. Further information about the importance of enhanced storage is given in chapter 6.

Distinction 6: On-site removal of solids
Removal of solids by means of on-site septic tanks from wastewater that has to be transported through sewers has several advantages and also some disadvantages (chapter 6). A distinction is made between system options without and with on-site removal of solids.

Distinction 7: On-site treatment of grey water in septic tanks
At the installation of a household septic tank and the construction of in-house plumbing households have the choice between connecting both black and grey water to the septic tank or black water alone with grey water by-passing the septic tank. A distinction is made between system options with or without co-treatment of grey water in the septic tank.

Distinction 8: Application of stormwater runoff treatment
In separate sewer systems a distinction is made between system options in which the stormwater runoff is discharged directly to surface water, and options with overflow devices that lead the collected stormwater to the wastewater-treatment plant at low and moderate rainfall intensities. Overflow of stormwater to surface water occurs only if the total flow exceeds the capacity of the treatment plant. The first is named the plain separate sewer system and the second the improved or integrated separate sewer system. These systems are discussed in chapter 6.

Distinction 9: Pumping of sewage
At sewage transport over long distances and in flat terrain pumping is needed to overcome head loss. A distinction is made between system options without and with pumping of sanitary sewage. The addition of the symbol (P) to an option number (such as 6A(P)) indicates that in the mentioned option the transport of sanitary sewage is aided by pumping.

In the next subsection 5.4.2 the first three distinctions are used to identify 12 different *groups* of drainage and sanitation system options (table 5.3, column 4). The remaining 6 distinctions differentiate the system options *within* the groups leading to 58 system options (table 5.3, column 7). References of the application of system options are given in table 5.4.

5.4.2 Drainage and sanitation system options

Among the *household and communal on-site and hybrid systems* three system groups, including 6 system options, indicated with the name of their toilet technology, are distinguished:

- System group 1: dry anaerobic toilets (options 1A, 1B);
- System group 2: urine-diverting dry toilets (options 2A, 2B);
- System group 3: low of high volume flush toilets (options 3A, 3B).

System group 1 encompasses in principle all dry anaerobic toilets, i.e. variations of pit latrines both in household and communal forms, such as VIP, raised pit latrine, alternating twin pit latrine and the anaerobic digestion toilet (Cairncross and Feachem, 1983, Chaggu, 2003). Group 2 covers the urine-diverting dehydration toilets. These dry toilets have been in use over a long time, most often in a rural setting where the collected urine and faecal matter could be directly utilized (Esrey et al., 1998, p 21, Hupping Stoner, 1977, p 2). Group 3 are system options with flush toilets and on-site treatment with septic tank and soakage pits (Mara, 1996). The systems of group 1 and 3 are very popular in developing countries and group 2 has been widely promoted during the last decade by virtue of its high potential degree of resource recovery (Winblad et al., 2004). In the system groups 1 until 3 a further distinction is made between options with household and communal toilets. Options 1A, 2A and 3A are household on-site systems and options 1B, 2B and 3B are communal systems (figures 5.5.1, 5.5.2 and 5.5.3).

The *off-site treatment systems* of system groups 4 until 7 can be applied as central and as community-based systems. They are grouped according to the application of regular flush toilets (high- or low-volume) or urine-diverting flush toilets and combined or separate transport of domestic sewage and stormwater. The following groups and system options are distinguished:

- System group 4 (options 4A-4F): high or low-volume flush toilets and combined transport of domestic sewage and stormwater;
- System group 5 (options 5A-5F): urine-diverting flush toilets and combined transport of brown water and stormwater;
- System group 6 (options 6A-6F and 6A(P)-6F(P): high or low-volume flush toilets and separate transport of domestic sewage and stormwater;
- System group 7 (options 7A-7F and 7A(P) – 7F(P) : urine-diverting flush toilets and separate transport of brown water and stormwater.

System groups 4 (combined sewerage) and 6 (separate sewerage) (figures 5.5.4 and 5.5.6) are common drainage and sanitation systems worldwide. The strengths and weaknesses of these two groups are discussed in detail in chapter 6. In The Netherlands separate transport of sewage and stormwater (group 6) is generally implemented in new residential areas, though combined transport and treatment is traditionally the most common system. System groups 5 and 7 (figures 5.5.5 and 5.5.7) have combined and separate sewer systems, but here urine is collected separately by using urine-diverting flush toilets and transported by cartage for further treatment and reuse. The possibilities of the urine-diverting flush toilets have been extensively researched in the framework of the Novaquatis project (www.novaquatis.eawag.ch). The advantage of this system is simple recovery of nitrogen and phosphorous from urine and considerable savings in nutrient removal during the effluent-treatment process.

Further distinctions of *system options* within groups 4 and 5 are made on the basis of application of *enhanced storage capacity* in the sewer system (distinction 5), the *on-site removal of wastewater solids* (distinction 6) and *on-site co-treatment of grey water* (distinction 7). The application of these distinctions lead to 6 system options within each system group: options 4A – F and options 5A-F (Appendix 1,tables 5.A.2 and 5.A.3). In Vietnamese cities the settled combined sewer system (options 4C and 4E) in particular is common.
The subdivision of the system groups 6 and 7 into system options applies the distinctions 8 and 9 (*stormwater treatment* and *pumping of sewage*) in addition to the distinctions *on-site removal of wastewater solids* (distinction 5) and *on-site co-treatment of grey water* (distinction 6). This leads to 12 system options in both group 6 and 7 (Appendix 1, table 5.A.4 and 5.A.5)

The *community-based off-site treatment systems* of system groups 8 until 12 are classified according to the use of urine-diverting and vacuum toilets and combined or separated transport of grey water and stormwater as follows:

- System group 8 (options 8A and 8B): urine-diverting dry toilets and combined transport of grey water and stormwater;
- System group 9 (options 9A and 9B): vacuum low-flush toilets, separated transport of concentrated black water and combined transport of grey water and stormwater;
- System group 10 (options 10A, 10B, 10A(P), 10B(P)): urine-diverting dry toilets and separated transport of grey water and stormwater;
- System group 11 (options 11A, 11B, 11A(P), 11B(P)): vacuum low-flush toilets and separated transport of concentrated black water, grey water and stormwater;
- System group 12 (options 12A, 12B, 12A(P), 12B(P)): urine-diverting flush toilets and separated transport of urine, black water, grey water and stormwater.

These system groups (8 until 12) with urine-diverting dry toilets, urine-diverting flush toilets and vacuum toilets are community-based systems, since it is assumed that the treatment and reuse of faecal matter and treated concentrated black water could best be organized at a local scale. Combinations of urine-diverting dry toilets with sewered transport of grey water and stormwater (groups 8 and 10) in densely built peri-urban areas are (still) rare. Vacuum low-flush toilets (groups 9 and 11) are an innovative technology that facilitates the concentrated collection, transport and reuse of concentrated black water. Systems of group 9 and 11 are being tested in The Netherlands and Germany respectively (Meulman et al., 2008; Oldenburg et al., 2008). A system belonging to group 12 with completely separated handling of all

source streams and reuse of treated urine and brown water is tested in the building of GTZ in Germany (Werner et al., 2008).
The subdivisions of these five system groups into system options make use of the same distinctions applied in the other system groups. This subdivision is shown in Appendix 1, table 5.A.6.

Fate of stormwater runoff
As shown above the different system groups have different ways to handle stormwater runoff. Column 6 of table 5.3 indicates the fate of stormwater run-off between the system groups. In the case of household on-site sanitation at low building density (system groups 1 until 3) the stormwater is most of the times infiltrated locally and carried away by natural drains. Stormwater runoff in densely built urban areas usually has to be transported by means of sewers. In the case of combined sewer systems stormwater and sewage (system groups 4 and 5) or stormwater and grey water (system groups 8 and 9) are transported and treated jointly, with incidental combined-sewer overflow (CSO) at high runoff intensities. If sewage (or grey water) and stormwater are transported separate (system groups 6, 7, 10, 11, 12), a distinction is made between system options in which the stormwater is diverted directly to surface water without treatment, and improved versions in which the stormwater is led to the wastewater-treatment plant via an overflow device. In the community-based systems with separation into 3 or 4 streams (system groups 11 and 12) the stormwater can be discharged without treatment, or, if necessary, be treated in a low-cost natural wastewater-treatment system like a constructed wetland.

Treatment
All drainage and sanitation system options reviewed here are supposed to protect public health in a sufficient way. In on-site sanitation excreta-related streams are either removed by cartage and treated off-site or treated onsite, while grey water (system groups 1 and 2) and septic-tank effluent (system group 3) are infiltrated to the subsoil via soakage pits. All off-site system options (system groups 4 until 7) have in common that they provide treatment of wastewater to at least secondary level. This implies that wastewater is subject to a two-stage treatment process consisting of primary solids removal and biodegradable organic matter removal with an efficiency of at least 85%. The community-based reuse-oriented system groups (system groups 8 until 12) are provided with suitable treatment technologies for the various waste streams. These technologies often have an experimental character. The treatment technologies are discussed in chapter 6.

Utilizable products
Utilizable products associated with the drainage and sanitation groups (table 5.3, column 5) are the treated effluent of the wastewater-treatment plants, urine, stabilized faecal sludges and biogas. A further discussion about reuse of valuable resources recoverable from different streams is presented in chapter 6.

Table 5.3 Overview of drainage and sanitation system options and their utilizable products.

Water supply (1)	Configuration (2)	System group Nr (3)	System options according segregation of waste streams (number of waste streams) (4)	Utilizable products (5)	Fate of stormwater (6)	System options Nrs (7)
Hand-carried	Household and communal on-site and hybrid sanitation	1	Dry anaerobic toilet systems in households and in communal toilet blocks, grey water infiltrated (3 streams)	Faecal sludge and biogas (communal systems)	Local infiltration and discharged without treatment	1A, 1B
		2	Urine-diverting dry toilet systems, grey water infiltrated (4 streams)	Urine, faecal matter, biogas (communal systems)		2A, 2B
Piped water supply		3	Low or high-volume flush toilets + on-site treatment of domestic sewage (2 streams)	Septic- tank sludge		3A, 3B
	Off-site treatment of sewage (Central and community-based)	4	Flush toilets, combined stormwater and sewage (1 stream)	Effluent, septic-tank sludge	Treated with domestic sewage/brown water and grey water	4A - 4F
		5	Urine-diverting flush toilets + urine collection, combined stormwater, brown and grey water (2 streams)	Effluent, septic-tank sludge, urine		5A - 5F
		6	Flush toilets, separate collection of stormwater and sewage (2 streams)	Effluent, septic-tank sludge	No treatment or treated with sewage or grey water	6A - 6F 6A(P) - 6F(P)
		7	Urine-diverting flush toilets + urine collection, separate collection of stormwater, brown + grey water (3 streams)	Effluent, septic-tank sludge, urine		7A - 7F 7A(P) - 7F(P)
	Off-site treatment of source-separated streams (Community-based)	8	Urine diverting dry toilets, separate collection of urine and faecal matter, combined storm- and grey water (3 streams)	Urine, faecal matter, effluent	Treated with grey water	8A, 8B
		9	Vacuum toilets + black water collection, combined storm- and grey water (2 streams)	Effluent, black water sludge, biogas	Treated with grey water	9A, 9B
		10	Urine-diverting dry toilets, separate collection of urine, faeces, grey water and stormwater (4 streams)	Urine, faecal matter, effluent	No treatment or treated with GW	10A, 10B 10A(P), 10B(P)
		11	Vacuum toilets, separate collection of black water, grey water and stormwater (3 streams)	Effluent, black water sludge, biogas	No treatment or treated with GW	11A, 11B 11A(P), 11B(P)
		12	Urine-diverting flush toilets, separate collection of urine, brown water, grey water and stormwater (4 streams)	Effluent, urine	No treatment or treated with GW	12A, 12B 12A(P), 12B(P)

Table 5.4 Practical application of drainage and sanitation system options.

Water supply	Configuration	System group Nr	System options according segregation of waste streams (number of waste streams)	Options Nrs	System application in practice
(1)	(2)	(3)	(4)	(5)	(6)
Hand-carried	Household and communal on-site and hybrid sanitation	1	Dry anaerobic toilet systems in households and in communal toilet blocks, grey water infiltrated (3 streams)	1A, 1B	Pit latrines (Cairncross and Feachem, 1983) Experimental system meant as improvement to the pit latrine (Chaggu, 2004)
		2	Urine-diverting dry toilet systems, greywater infiltrated (4 streams)	2A, 2B	Projects in many countries (Winblad and Simpson-Hébert, 2004)
Piped water supply		3	Low or high-volume flush toilets + on-site treatment of domestic sewage (2 streams)	3A, 3B	System 3A: widely spread all over the world (Mara, 1996b)
	Off-site treatment of sewage (Central and community-based)	4	Flush toilets, combined stormwater and sewage (1 stream)	4A - 4F	Systems 4A and 4B: common in towns Systems 4C, 4E: common in Vietnam (without WWTP)
		5	Urine-diverting flush toilets + urine collection, combined stormwater, brown and grey water (2 streams)	5A - 5F	Experimental system (Novaquatis, EAWAG)
		6	Flush toilets, separate collection of stormwater and sewage (2 streams)	6A - 6F 6A(P)-6F(P)	Systems 6A and 6B: common all over the world System 6C, 6D: in Vietnamese cities (e.g. Da Lat)(Corning, 2006)
		7	Urine-diverting flush toilets + urine collection, separate collection of stormwater, brown + grey water (3 streams)	7A - 7F 7A(P) -7F(P)	Unknown
	Off-site treatment of source-separated streams (Community-based)	8	Urine-diverting dry toilets, separate collection of urine and faecal matter, combined storm- and grey water (3 streams)	8A, 8B	Unknown
		9	Vacuum toilets + black water collection, combined storm- and greywater (2 streams)	9A, 9B	System 9A: The Netherlands (Meulman et al., 2008)
		10	Urine-diverting dry toilets, separate collection of urine, faeces, grey water and stormwater (4 streams)	10A, 10B 10A(P), 10B(P)	Unknown
		11	Vacuum toilets, separate collection of black water, grey water and stormwater (3 streams)	11A, 11B 11A(P), 11B(P)	System 11A: Germany (Oldenburg et al., 2008)
		12	Urine-diverting flush toilets, separate collection of urine, brown water, grey water and stormwater (4 streams)	12A, 12B 12A(P), 12B(P)	System 12A: (Peter-Froehlich et al., 2007); GTZ building, Germany (Werner et al., 2008)

5.5 Overview of system options

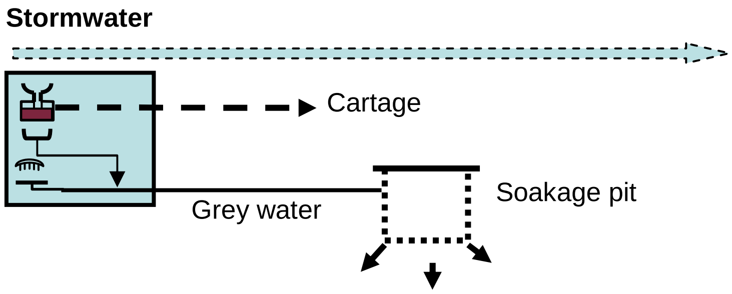
Systematic combination of the drainage and sanitation technologies, taking into account mutually exclusive and unlikely system options across the 12 groups distinguished in table 5.3 and 5.4 has yielded in total 58 options.

- 3 household on-site (options 1A, 2A and 3A);
- 3 communal on-site (options 1B, 2B and 3B);
- 6 systems with flush toilets and combined sewer systems (options 4A-F);
- 6 systems with urine-diverting flush toilets and combined sewer systems (options 5A-F);
- 12 systems with flush toilets and separated sewer systems (options 6A-F(P));
- 12 systems with urine- diverting flush toilets and separated sewers (options 7A-F(P));
- 4 community-based off-site systems having urine-diverting dry toilets (groups 8 and 10);
- 8 systems with low-volume vacuum toilets (groups 9 and 11);
- 4 systems with urine-diverting flush toilets and separation of four waste streams (group 12).

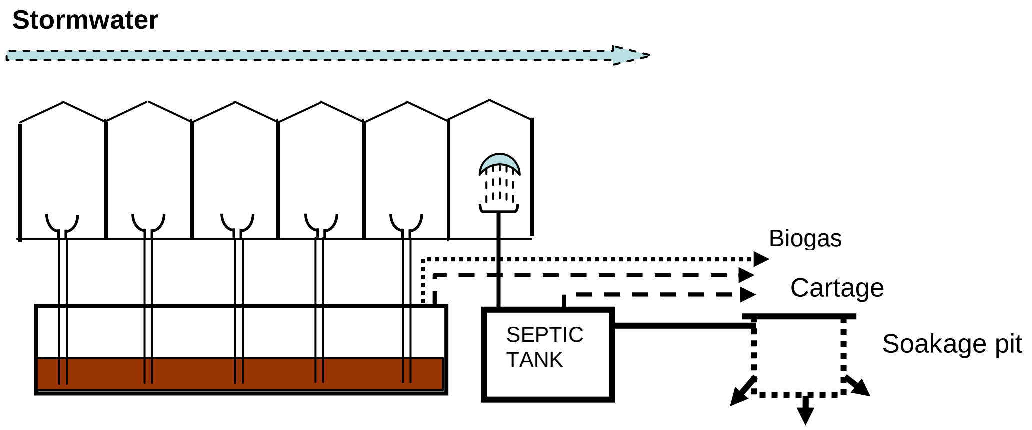
Schematic representations of all system groups are shown in the figures of this section below. At all system options mention is made of:

- the number of the option;
- the name of the option;
- the number of separate waste streams that have to be transported and treated/disposed. Here, septic-tank sludge is not considered as a separate waste stream.

All system options with separate sewer systems can be provided where necessary with pumping devices for sewage. These options are indicated with the addition of the symbol (P) to the option number. The example of option 7F(P) is shown in figure 5.3 above.

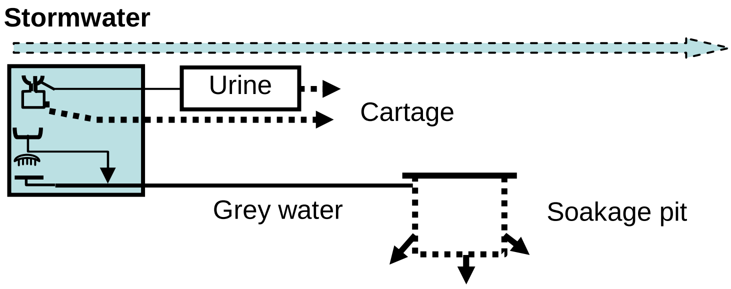


Option 1A: Dry accumulating anaerobic digestion toilet + cartage;
grey water to subsoil;
(3 waste streams)

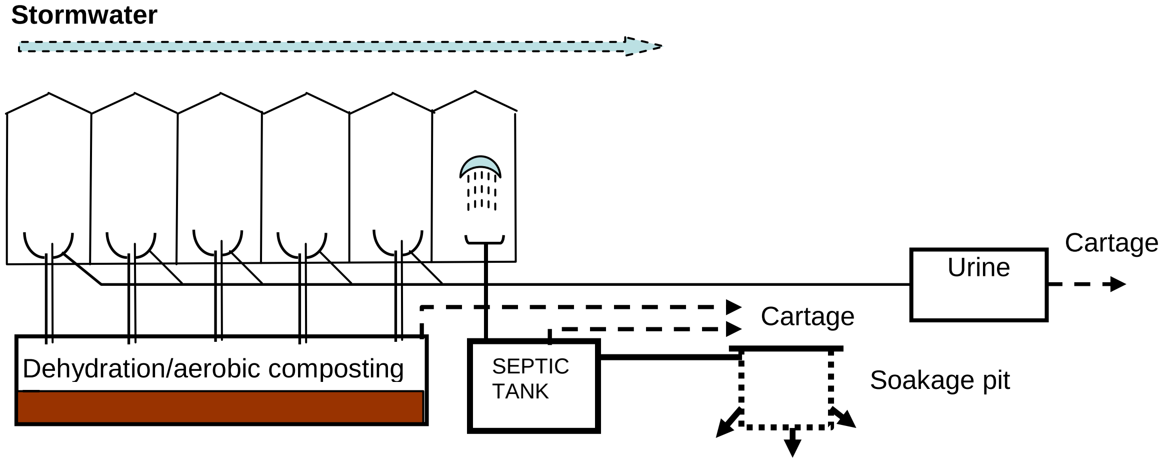


Option 1B: Communal dry toilets + accumulating anaerobic digester
+ cartage; grey water to subsoil; utilization of biogas;
(3 waste streams)

Figure 5.5.1
System group 1
Household and communal dry anaerobic toilets, on-site treatment of grey water.

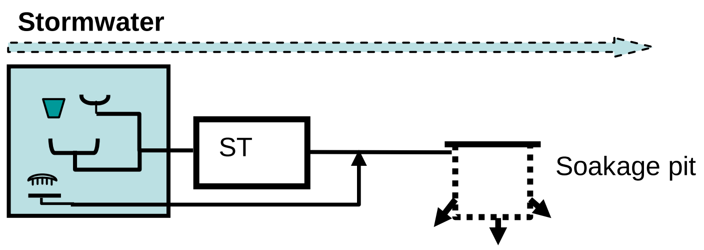


Option 2A: Urine-diverting dry toilet + cartage of urine and faecal matter; grey water to subsoil; (4 waste streams)

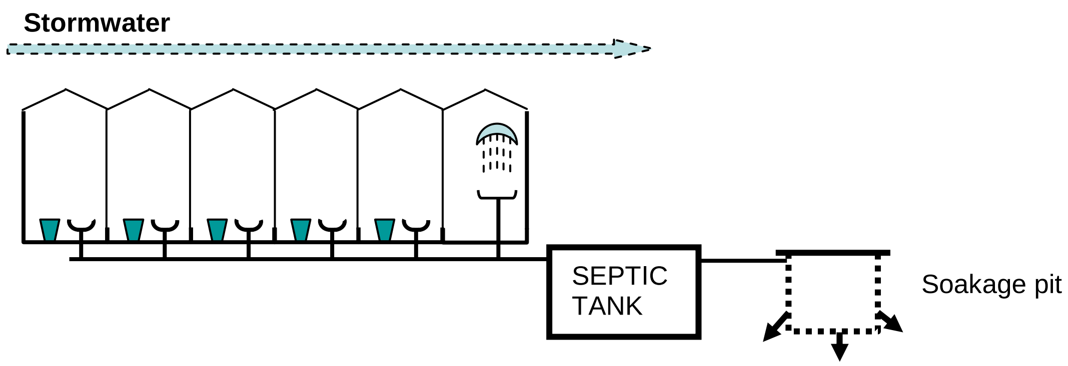


Option 2B: Communal urine-diverting dry toilets, cartage of urine, faecal matter and sludge; grey water to subsoil; (4 waste streams)

Figure 5.5.2
System group 2
Household and communal urine-diverting dry toilets, cartage of urine and faecal matter, on-site treatment of grey water.



Option 3A: Flush toilet + septic tank + soakage pit;
cartage of septic-tank sludge; septic-tank effluent to subsoil;
(2 waste streams)



Option 3B: Communal flush toilets + septic tank + soakage pit;
cartage of septic-tank sludge; septic-tank effluent to subsoil;
(2 waste streams)

Figure 5.5.3
System group 3
Household and communal low or high-volume flush toilets with on-site treatment of domestic sewage (ST = Septic Tank).

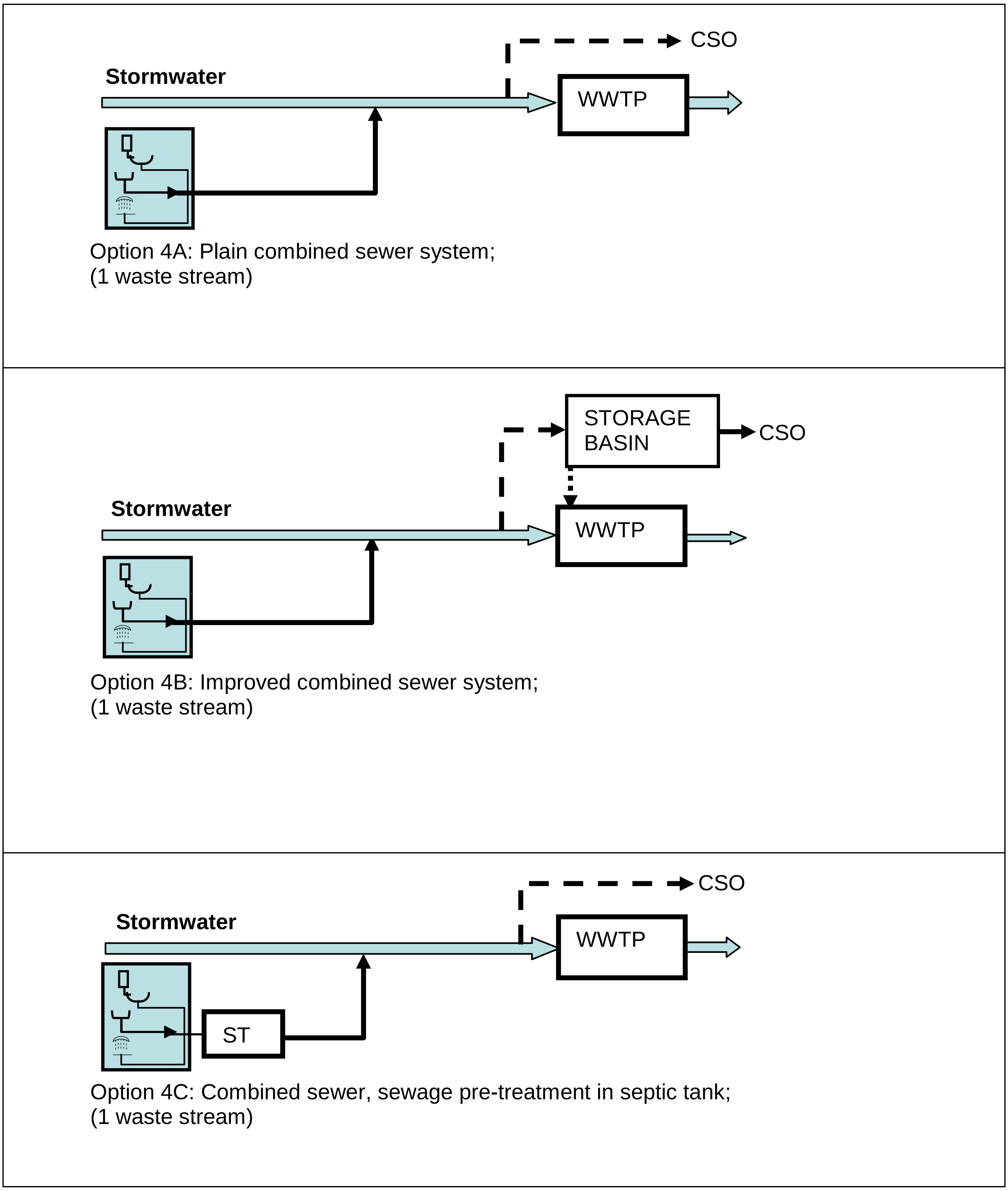
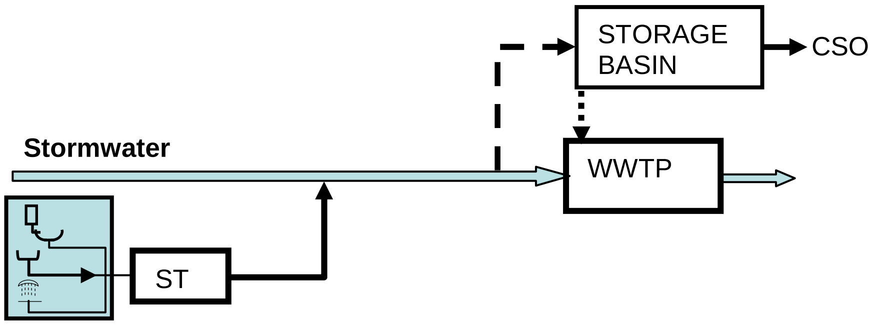
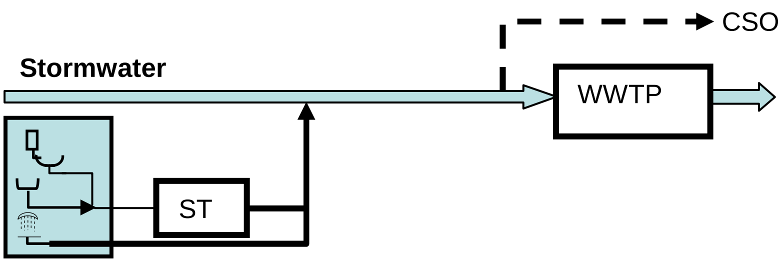


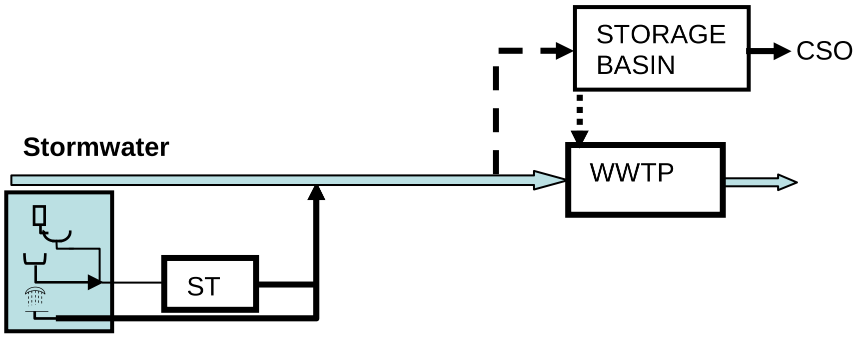
Figure 5.5.4
System group 4
Flush toilets and combined collection of stormwater and sewage (CSO = Combined Sewage Overflow; ST = Septic Tank; WWTP = Wastewater Treatment Plant).



Option 4D: Improved settled combined sewer system;
(1 waste stream)

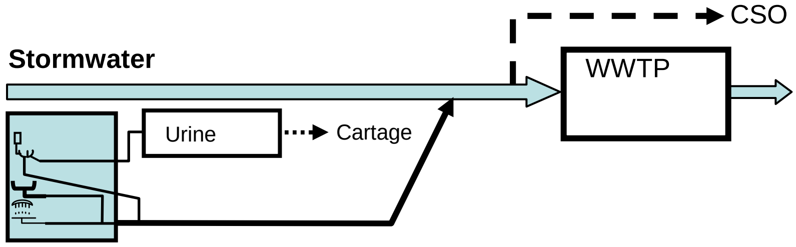


Option 4E: Settled combined sewer system with grey water bypass;
(1 waste stream)

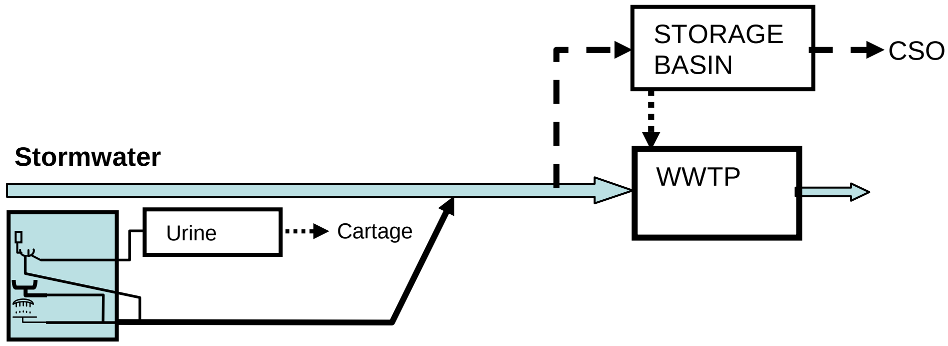


Option 4F: Improved settled combined sewer system with grey water bypass;
(1 waste stream)

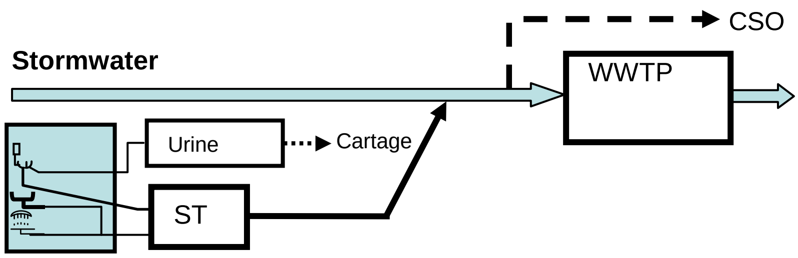
Figure 5.5.4
System group 4 (continued)
Flush toilets and combined collection of stormwater and sewage (CSO = Combined Sewage Overflow; ST = Septic Tank; WWTP = Wastewater Treatment Plant).



Option 5A: Urine-diverting flush toilets; urine cartage;
Combined sewer system;
(2 waste streams)

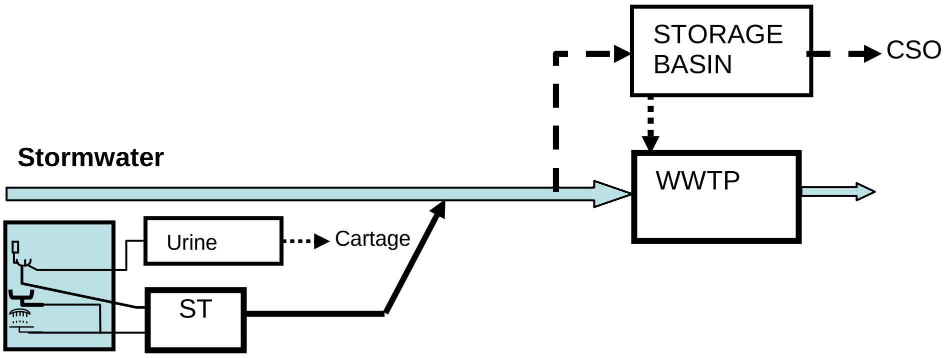


Option 5B: Urine-diverting flush toilets; urine cartage;
improved combined sewer system;
(2 waste streams)

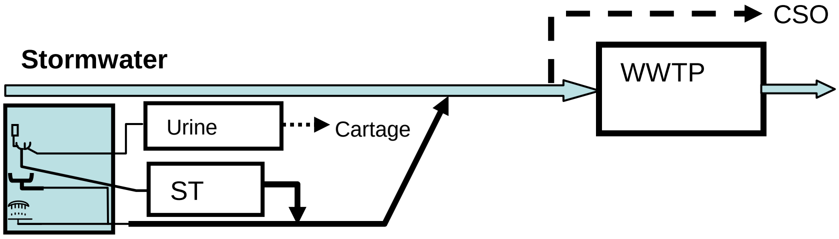


Option 5C: Urine-diverting flush toilets; urine cartage;
settled combined sewer system;
(2 waste streams)

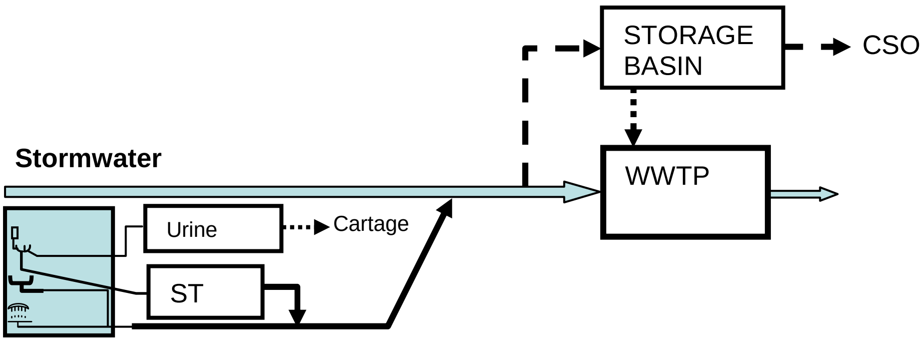
Figure 5.5.5
System group 5:
Urine-diverting flush toilets and urine collection, combined collection of stormwater, brown water and grey water (CSO = Combined Sewage Overflow; ST = Septic Tank; WWTP = Wastewater Treatment Plant).



Option 5D: Urine-diverting flush toilets; urine cartage; improved settled combined sewer system ; (2 waste streams)



Option 5E: Urine-diverting flush toilets; urine cartage; settled combined sewer system with grey water bypass; (2 waste streams)



Option 5F: Urine-diverting flush toilets; urine cartage; improved settled combined sewer system with grey water bypass; (2 waste streams)

Figure 5.5.5
System group 5 (continued)
Urine-diverting flush toilets and urine collection, combined collection of stormwater, brown water and grey water (CSO = Combined Sewage Overflow; ST = Septic Tank; WWTP = Wastewater Treatment Plant).

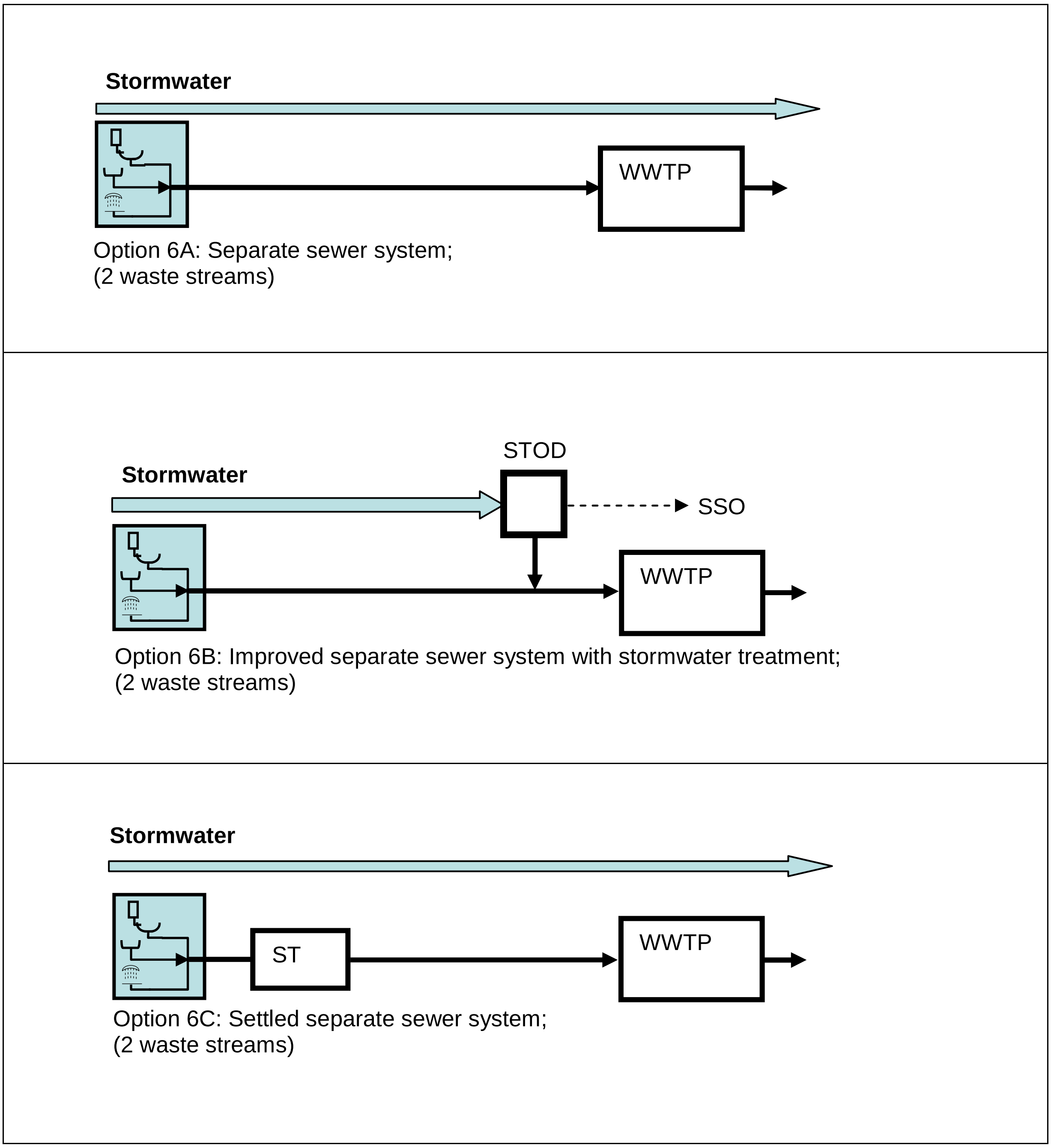
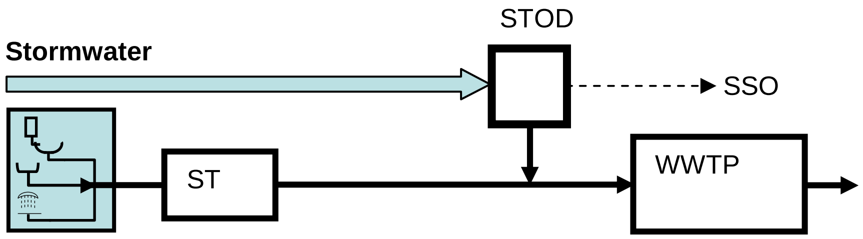
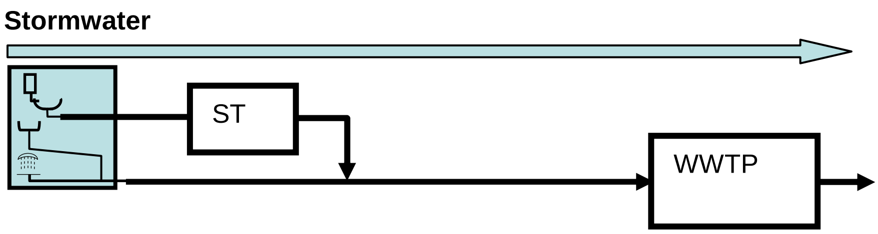


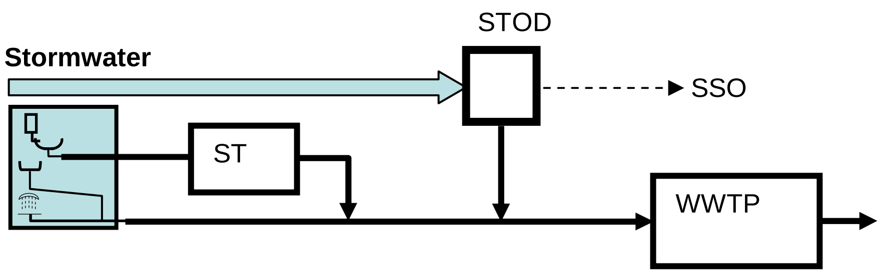
Figure 5.5.6
System group 6
Flush toilets and separate collection of stormwater and sewage (SSO = Storm Sewer Overflow; ST = Septic Tank; STOD = Stormwater Overflow Device; WWTP = Wastewater Treatment Plant).



Option 6D: Improved settled separate sewer system with stormwater treatment;
(2 waste streams)

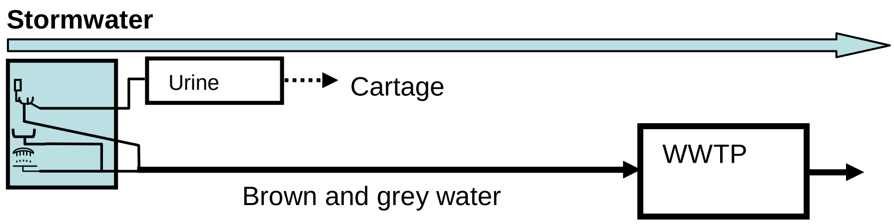


Option 6E: Settled separate system with grey water bypass;
(2 waste streams)

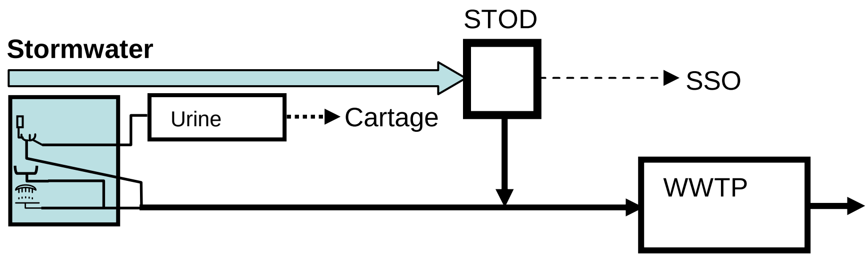


Option 6F: Improved settled separate system with grey water bypass;
(2 waste streams)

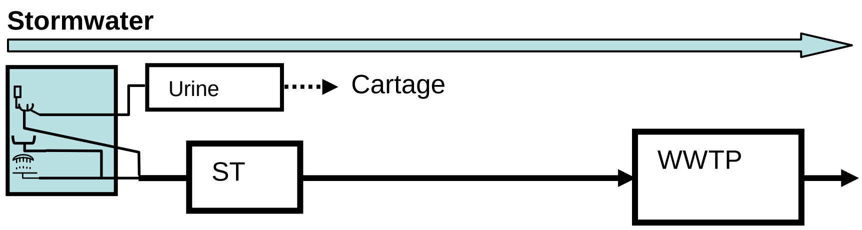
Figure 5.5.6
System group 6 (continued)
Flush toilets and separate collection of stormwater and sewage (SSO = Storm Sewer Overflow; ST = Septic Tank; STOD = Stormwater Overflow Device; WWTP = Wastewater Treatment Plant).



Option 7A: Urine-diverting flush toilets; urine cartage;
plain separate system;
(3 waste streams)

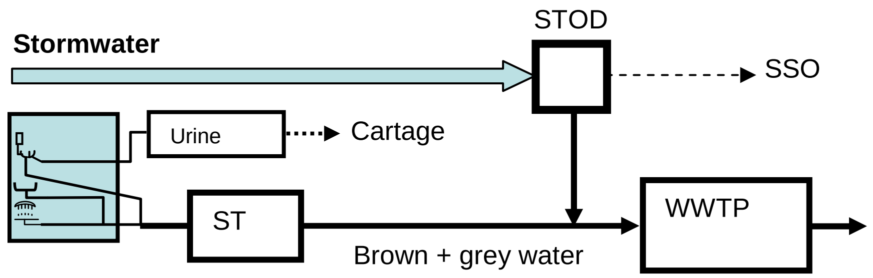


Option 7B: Urine-diverting flush toilets; urine cartage;
improved separate system;
(3 waste streams)

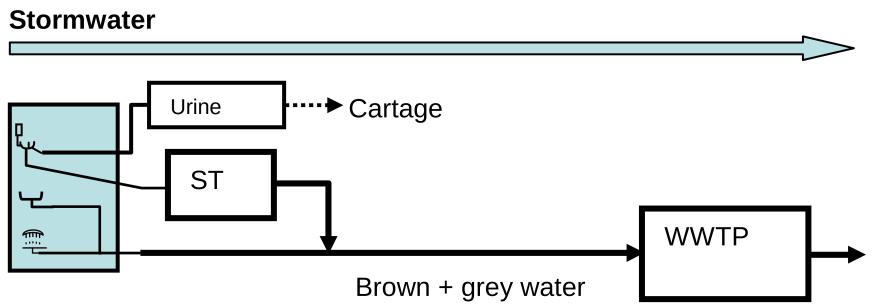


Option 7C: Urine-diverting flush toilets; urine cartage;
settled separate system;
(3 waste streams)

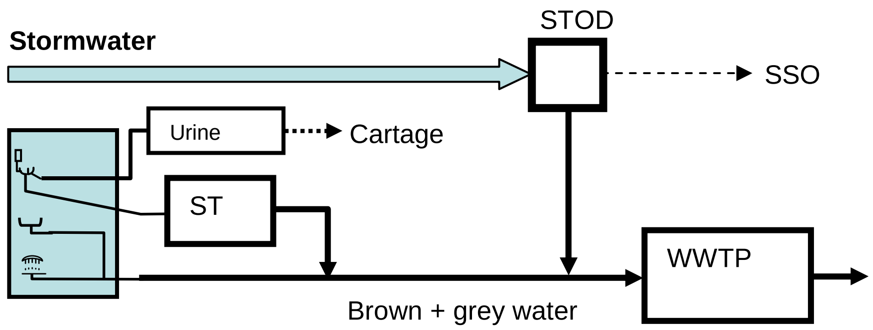
Figure 5.5.7
System group 7
Urine-diverting flush toilets and urine collection, separated collection of stormwater and brown + grey water (SSO = Storm Sewer Overflow; ST = Septic Tank; STOD = Stormwater Overflow Device; WWTP = Wastewater Treatment Plant).



Option 7D: Urine-diverting flush toilets; urine cartage;
improved settled separate sewer system;
(3 waste streams)

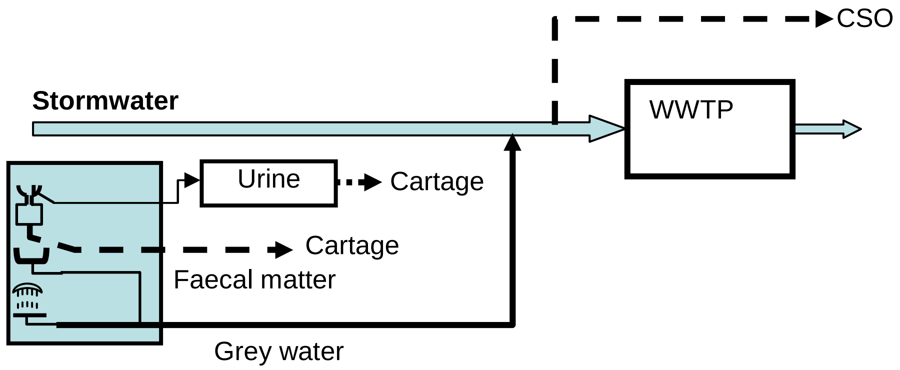


Option 7E: Urine-diverting flush toilets; urine cartage;
settled separate system; brown water treated in septic tank;
(3 waste streams)

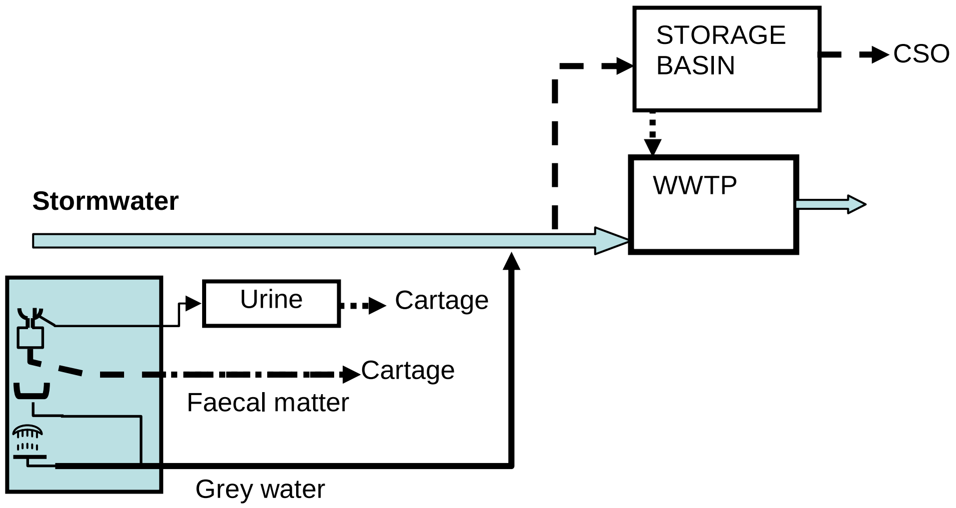


Option 7F: Urine-diverting flush toilets; urine cartage;
improved settled separate system; brown water treated in septic tank;
(3 waste streams)

Figure 5.5.7
System group 7 (continued)
Urine-diverting flush toilets and urine collection, separated collection of stormwater and brown + grey water (SSO = Storm Sewer Overflow; ST = Septic Tank; STOD = Stormwater Overflow Device; WWTP = Wastewater Treatment Plant).

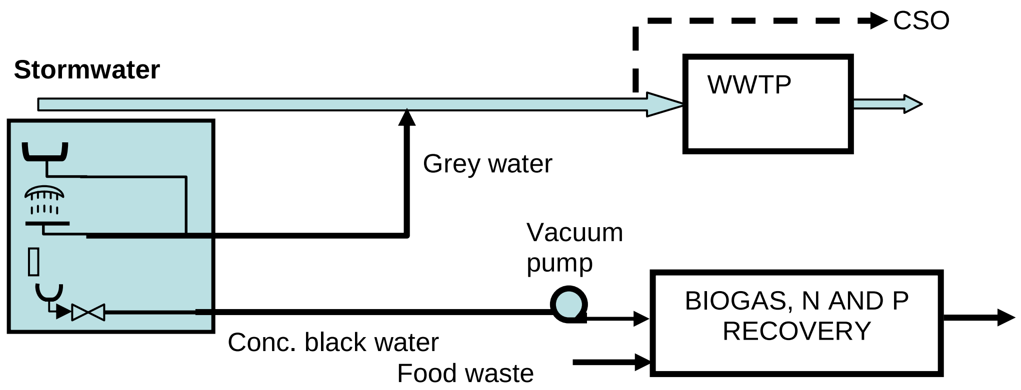


Option 8A: Dry urine-diverting toilets + combined settled sewer system;
cartage of urine and faecal matter;
(3 waste streams)

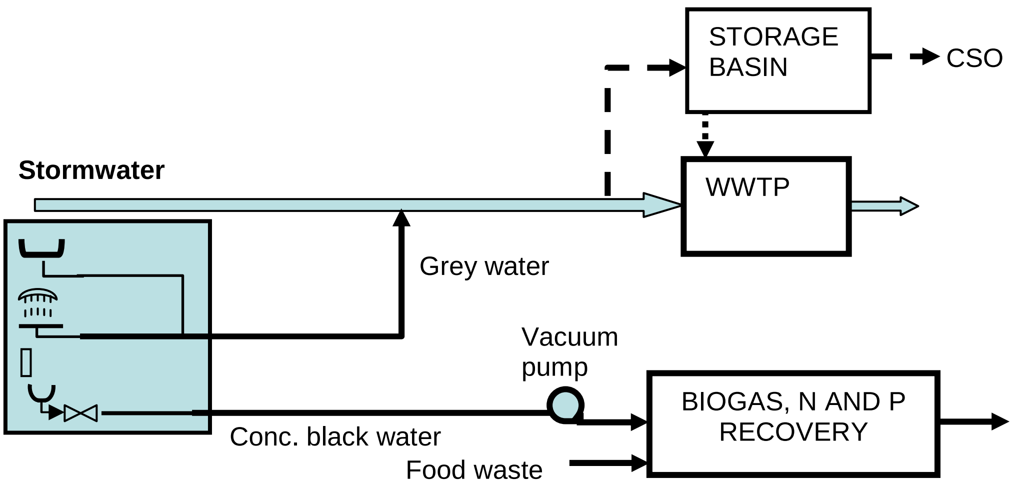


Option 8B: Dry urine-diverting toilets + improved combined settled sewer system;
cartage of urine and faecal matter;
(3 waste streams)

Figure 5.5.8
System group 8
Urine-diverting dry toilets, separated collection of urine and faecal matter, combined collection of grey water and stormwater (CSO = Combined Sewage Overflow; ST = Septic Tank; WWTP = Wastewater Treatment Plant).

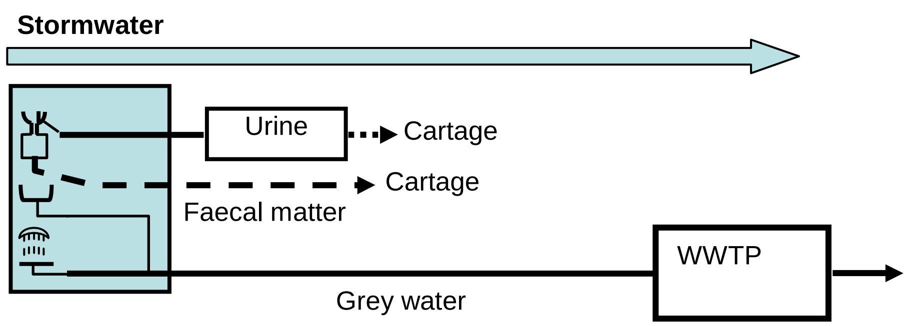


Option 9A: Vacuum toilets + biogas, N and P recovery;
combined treatment of storm- and grey water;
feeding of food waste;
(2 waste streams)

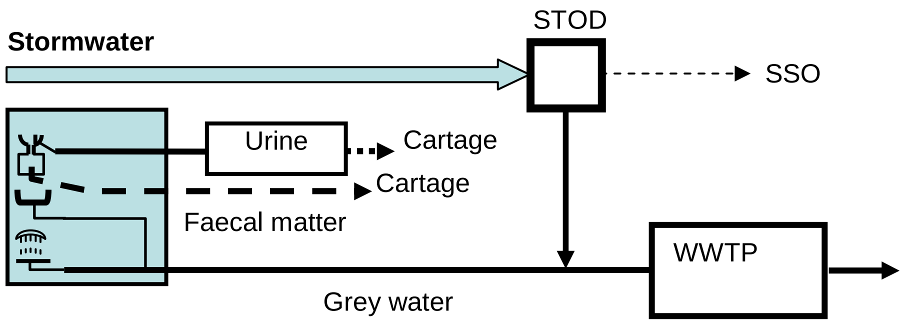


Option 9B: Vacuum toilets + biogas, N and P recovery;
combined treatment of storm- and grey water;
feeding of food waste;
(2 waste streams)

Figure 5.5.9
System group 9
Vacuum low-flush toilets, separate collection of black water and combined collection of grey water and stormwater (CSO = Combined Sewage Overflow; ST = Septic Tank; WWTP = Wastewater Treatment Plant).



Option 10A: Dry urine-diverting toilets + settled separate sewer system;
cartage of urine and faecal matter;
(4 waste streams)



Option 10B: Dry urine-diverting toilets + improved settled separate sewer system;
cartage of urine and faecal matter;
(4 waste streams)

Figure 5.5.10
System group 10
Urine-diverting dry toilets and separate collection of urine, faecal matter, grey water and stormwater (SSO = Storm Sewer Overflow; ST = Septic Tank; STOD = Stormwater Overflow Device; WWTP = Wastewater Treatment Plant).

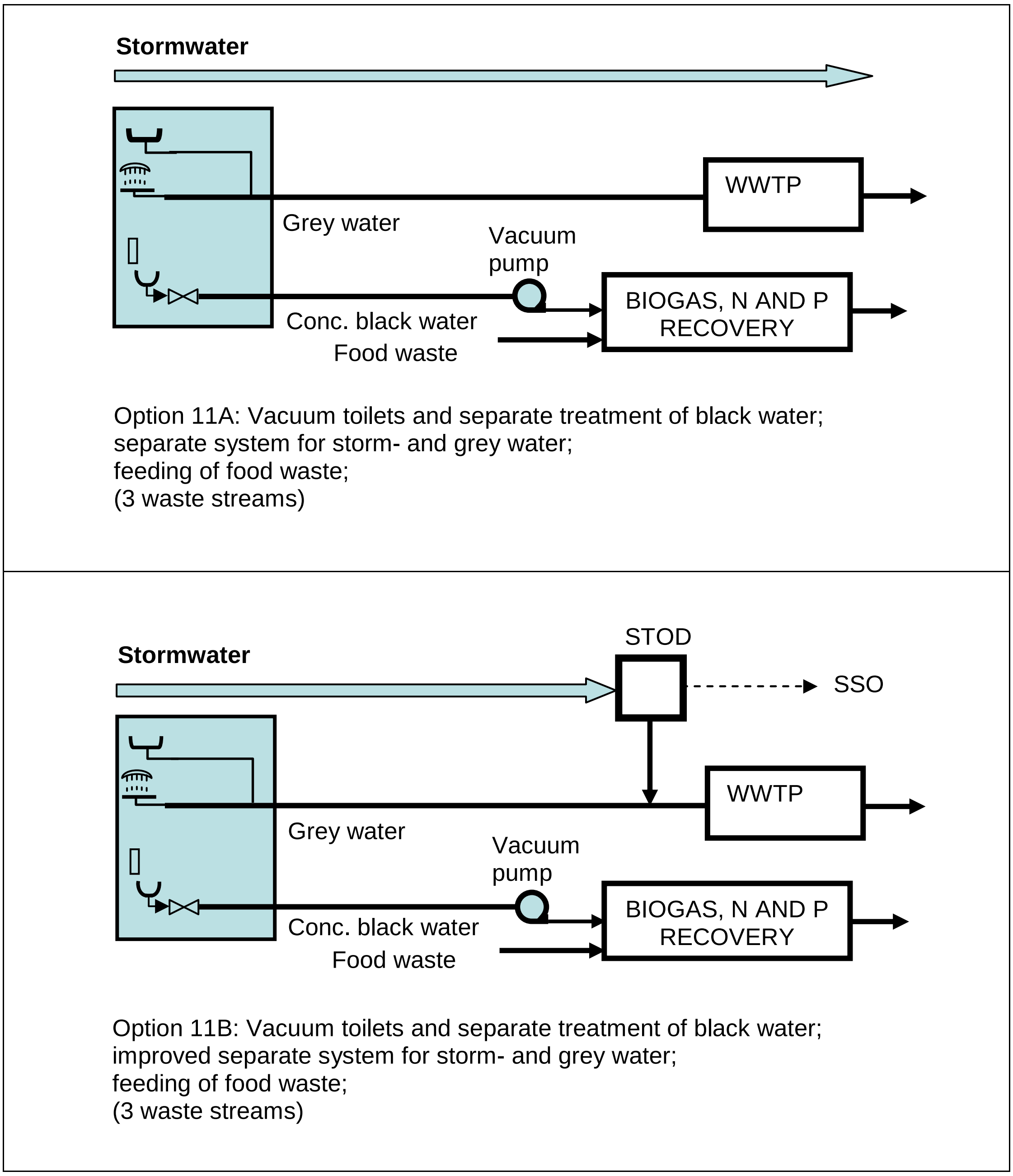
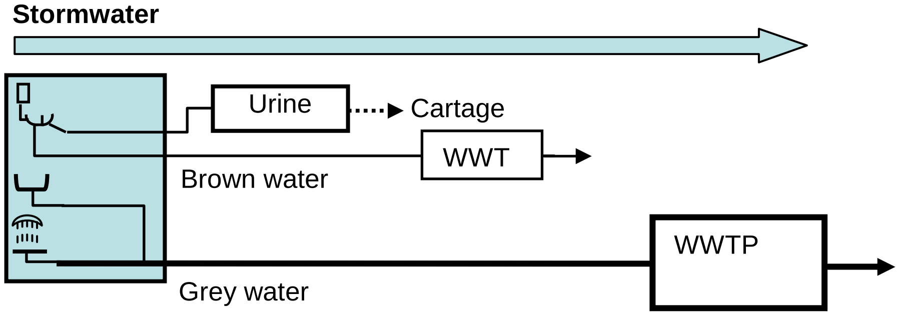
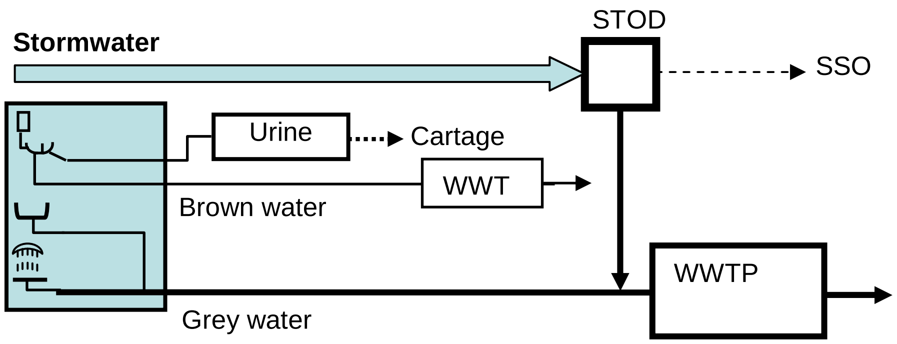


Figure 5.5.11
System group 11
Vacuum toilets, separate collection of black water, grey water and stormwater (SSO = Storm Sewer Overflow; ST = Septic Tank; STOD = Stormwater Overflow Device; WWTP = Wastewater Treatment Plant).



Option 12A: Urine-diverting flush toilets; cartage of urine;
separate collection and treatment of brown water and grey water;
(4 waste streams)



Option 12B: Urine-diverting flush toilets; cartage of urine;
separate collection and treatment of stormwater, brown water and grey water
(4 waste streams)

Figure 5.5.12
System group 12
Urine-diverting flush toilets, separated collection of urine, brown water, grey water and stormwater (SSO = Storm Sewer Overflow; ST = Septic Tank; STOD = Stormwater Overflow Device; WWTP = Wastewater Treatment Plant).

Pumped transport

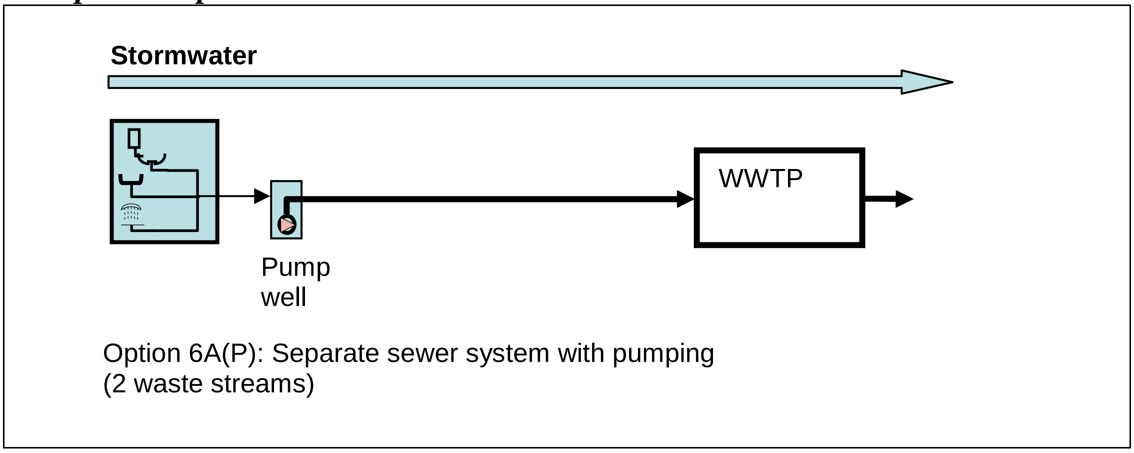


Figure 5.5.13 System option 6A(P) of group 6: flush toilets and separate transport of domestic sewage (pumped) and stormwater.

5.6 Conclusions

The present chapter gives an overview of drainage and sanitation system options to be used in the SANCHIS method. An attempt is made to represent the systems in a simple schematic way, so that the characteristics are clear at a glance and well applicable in participatory multi-criteria decision analysis. In chapter 3 several sanitation decision aids described in literature were characterized and compared. The overview given in this chapter 5 is partly similar, but in certain respects also different from the options lists used in these published decision aids. While the decision aids SANEX® (Loetscher, 1999), NETSSAF (Zurbruegg and Tilley, 2007) and EAWAG compendium (Tilley et al., 2008) put emphasis on household on-site methods, the present overview reduces the number of household on-site systems and widens the choice of regular and innovative sewered systems. This focus on sewered systems is justified by the high building density of urban areas in Vietnam and other developing countries for which the SANCHIS method has been designed. The described off-site systems can be applied both at community and central scale.

Since the SANCHIS method not only is a tool for participatory system selection, but also intends to inform a learning process about new developments, ample attention is given to innovative reuse-oriented systems despite their often experimental character.

Drainage and sanitation systems have a long life-time. This requires serious consideration of approaches and systems that may look futuristic at present, but could become mainstream and legally prescribed soon.

Appendix of chapter 5 Overview of drainage and sanitation system options

The tables 5.A.1 until 5.A.6 in this appendix give an overview of the systematic application of the distinctions mentioned in this chapter to classify the drainage and sanitation system options used in the SANCHIS method, subdivided into 12 system groups according to table 5.3. In these tables the following symbols are used.

Symbol	Explanation
0	Not available
+	Available

Table 5.A.1 System options for household and communal on-site treatment
(HOS = household on-site; COS = communal on-site; dAAD = dry accumulating anaerobic digestion; dUD = dry urine-diverting; PF = pour-flush; SP = soakage pit).

System component	System group 1		System group 2		System group 3	
	1A	1B	2A	2B	3A	3B
Location of toilets	HOS	COS	HOS	COS	HOS	COS
Toilet type	dAAD	dAAD	dUD	dUD	PF	PF
Grey water disposal	SP	SP	SP	SP	SP	SP
Nr of wastewater streams	3	3	4	4	2	2

Table 5.A.2 System options with pour-flush, cistern-flush toilets, collection of stormwater, black water and grey water in a single pipe system (combined sewer systems).

System component	System group 4 Gravity flow: system options 4A – F					
	4A	4B	4C	4D	4E	4F
Combined sewage retention basins	0	+	0	+	0	+
Septic tanks for black and grey water	0	0	+	+	0	0
Septic tanks with grey- water bypass	0	0	0	0	+	+
Urine diversion	0	0	0	0	0	0
Nr of wastewater streams	1	1	1	1	1	1

Table 5.A.3 System options with urine-diverting flush toilets, collection of stormwater, black water and grey water in a single pipe system.

System component	System group 5 Gravity flow: system options 5A-F					
	5A	5B	5C	5D	5E	5F
Combined sewage retention basins	0	+	0	+	0	X
Septic tanks for brown and greywater	0	0	+	+	0	0
Septic tanks with grey water bypass	0	0	0	0	+	+
Urine diversion	+	+	+	+	+	+
Nr of wastewater streams	2	2	2	2	2	2

Table 5.A.4 System options with pour-flush and cistern flush toilets. Stormwater and sewage collection in a double pipe network (separate sewerage).

System component	System group 6 Gravity flow: system options 6A-F Pumped flow: system options 6A(P)-6F(P)					
	6A 6A(P)	6B 6B(P)	6C 6C(P)	6D 6D(P)	6E 6E(P)	6F 6F(P)
Stormwater treated in wastewater - treatment plant	0	+	0	+	0	+
Septic tanks	0	0	+	+	0	0
Septic tanks with grey water bypass	0	0	0	0	+	+
Urine diversion	0	0	0	0	0	0
Nr of wastewater streams	2	2	2	2	2	2

Table 5.A.5 System options with urine-diverting flush toilets. Stormwater and sewage collection in a double pipe network (separate sewerage).

System component	System group 7 Gravity flow: system options 7A-F Pumped flow: system options 7A(P)-7F(P)					
	7A 7A(P)	7B 7B(P)	7C 7C(P)	7D 7D(P)	7E 7E(P)	7F 7F(P)
Stormwater treated in wastewater-treatment plant	0	+	0	+	0	+
Septic tanks for brown water and grey water	0	0	+	+	0	0
Septic tanks with grey water bypass	0	0	0	0	+	+
Urine diversion	+	+	+	+	+	+
Nr of wastewater streams	3	3	3	3	3	3

Table 5.A.6 Reuse-oriented system options with urine-diverting and vacuum toilets for community drainage and sanitation.

System component	System group 8		System group 9		System group 10		System group 11		System group 12	
	8A	8B	9A	9B	Gravity flow: system options 10A/B, 11A/B, 12A/B Pumped flow: system options 10A/B(P), 11A/B(P), 12A/B(P)					
Urine-diverting dry toilet	+	+	0	0	+	+	0	0	0	0
Low-flush vacuum toilet	0	0	+	+	0	0	+	+	0	0
Urine-diverting flush toilet	0	0	0	0	0	0	0	0	+	+
Combined transport of stormwater and grey water	+	+	+	+	0	0	0	0	0	0
Separated transport of stormwater and grey water	0	0	0	0	+	+	+	+	+	+
Integrated stormwater treatment	0	0	0	0	0	+	0	+	0	+
Combined sewage retention basins	0	+	0	+	0	0	0	0	0	0
Septic tanks for grey water	0	0	0	0	0	0	0	0	0	0
Nr of wastewater streams	3	3	2	2	4	4	3	3	4	4

CHAPTER 6 DRAINAGE AND SANITATION TECHNOLOGIES AND TECHNOLOGY CHAINS

6.1 Introduction

Chapter 5 introduces twelve groups of drainage and sanitation system options, which can be seen as a combination of 'technologies' or 'building blocks' performing a chain of processes. The drainage and sanitation chains start with the generation of the source streams (urine, faeces, black water, grey water and stormwater) and end with the delivery of final products which can be discharged or utilized (table 5.4). The aim of this chapter is to support the selection of systems and technologies. As such it forms a part of the SANCHIS data base elaborated in the chapters 3 until 7. As each system option consists of a chain of technologies: toilets, on-site storage and treatment, collection, treatment and reuse or disposal, the option as a totality should be judged by the characteristics of its composing 'links' and by the way these links act together. Accordingly, this chapter describes the performance of technologies with respect to technical, health and environmental aspects. These are aspects that are primarily determined by the technology and not by the situation in which they are applied.
The description follows the order of the processes in the management of wastewater: household appliances (6.2), on-site treatment (6.3), transport (6.4), off-site treatment (6.5) and utilization of valuable products (6.6). With exception of the last one, each of these sections ends with a screening matrix and an indication of the consequences of the technology for the chain as a whole in order to facilitate the technology choice. The screening matrix may help to find out whether a technology can or can not be implemented in a situation under study. Section 6.7 contains a decision aid for selection at system level. In the concluding section 6.8 the outcomes of the chapter are summarized.

6.2 Household appliances

This section about household appliances introduces 6 toilet types (6.2.1), other household appliances (6.2.2), the impact of restrictive factors on implementability (6.2.3) and the strengths, weaknesses and conditions of most appropriate application of the toilet types (6.2.4).

6.2.1 Toilet options

Toilets in combination with the water-supply system determine the sanitation chain. Table 6.2.1 summarizes the different toilet technologies applied in the 12 system groups of drainage and sanitation systems introduced in chapter 5. The toilet types are: the *dry anaerobic digestion toilet*, *urine-diverting dry toilets*, *pour-flush* and *cistern-flush toilets*, *urine-diverting flush toilets (no mix toilets), and vacuum toilets*. The characteristics, strength and weaknesses and the application of these toilets are described below.

Table 6.2.1 Toilet types applied in the systems overview.

Toilet types	Drainage and sanitation system group	Application
Dry anaerobic digestion toilet	1	Household and community on-site sanitation without piped water supply
Urine-diverting dry toilet	2, 8, 10	
Pour-flush toilet	3, 4, 6	Household on-site and sewered systems
Cistern-flush toilet	3, 4, 6	
Urine-diverting flush toilet	5, 7, 12	Sewered systems
Vacuum toilet	9, 11	

6.2.1.1 Dry anaerobic toilets

Dry toilets do not use water for the transport of excreta and are the most simple toilet technology in which excreta (urine, faeces and anal cleansing material) are stored in a pit or container and left to partial anaerobic stabilization on-site. Once the storage space is full, it has to be emptied or to be abandoned. There are many subtypes, such as simple pit latrines (PL), ventilated improved pit latrines (VIP), alternating twin pit latrines, raised latrines, vault toilets, etc.) (Winblad and Simpson-Hébert, 2004). An important distinction between several dry toilet types is the fate of leachate. In simple pit latrines and the ventilated improved pit latrine the leachate seeps into the subsoil thereby causing pollution of soil and groundwater which may jeopardize human health and the environment, particularly at a high building density and where shallow wells are in use. Here, special mention is made of the *dry accumulating anaerobic digestion (DAAD) toilet*, a dry toilet on top of a closed tank in which the urine, faeces and possibly anal cleansing water are introduced at the bottom of the storage tank and treated by anaerobic processes (system options 1A and 1B). There is no discharge to the soil or a piped network. The accumulated slurry is carted away, treated and utilized. In a demonstration DAAD system in Tanzania the black-water production was assumed to be 2.1 l/cap.d[17] (Chaggu, 2004). A family of 5 people would produce about 4 m^3 of faecal sludge annually, so that the transport costs of this system could be considerable, if the slurry has to be transported over a long distance. Biogas utilization will in practice be feasible only in communal systems (option 1B). Addition of animal manure or other biowastes could render biogas utilization more worthwhile. The escape of the greenhouse gas methane to the atmosphere can be a serious disadvantage of anaerobic toilets. Special attention has to be paid to pathogenic organisms in the sludge and prevention of insect nuisance. Pit latrines are widely used in rural and low-income urban areas in developing countries.

6.2.1.2 Urine-diverting dry toilets

Urine-diverting dry toilets (often named Ecosan toilets) are designed to keep urine and faeces separate, so that they can be easily transported, treated and reused. In contrast to the excreta collected from pit latrines, the faecal matter collected separately from urine can be dried and transported without much effort and safely. In areas with a high risk of flooding the toilets are built on a pedestal, so that the toilet itself and the storage containers for faecal matter and urine stay dry. In principle, the source-separated faecal matter can be stored and treated either in an aerobic or an anaerobic way. For aerobic on-site treatment usually ash, sawdust or other

[17] Total volume of black water (liters/cap.d) is made up from 1.25 liter of urine, 0.15 kg of faecal matter and 0.75 liter of flush water (Chaggu, 2004).

water-absorbing and carbon-rich material is added after toilet use. Subsequently, the volume of the faecal matter decreases in the storage compartment, due to aerobic conversion and dehydration. A lack or high price of such water-absorbing material may limit the use of this type of toilet. Anal cleansing water should be collected and treated separately ((Werner et al., 2007). The transport of the urine and faecal matter takes place by cartage. The concept goes back to the double-vault composting toilet, which is still used in Vietnam (Nghien and Calvert, 2000). Worldwide, many improved versions have been developed, that make the system suitable for in-house use (Winblad and Simpson-Hébert, 2004).

The urine-diverting dry (Ecosan) toilet has considerable environmental and cost advantages, but can also demonstrate weaknesses, such as problems with insects and odours, and insufficient user acceptance. This toilet system has been introduced in rural and peri-urban areas in many parts of the world. It seems especially successful where there is a lack of water and a direct need of the nutrients from urine and faecal matter in local crop cultivation.

Urine-diverting dry toilets are applied in drainage and sanitation system groups 2, 8 and 10.

6.2.1.3 Pour-flush toilets

In *pour-flush* toilets urine and faecal matter are flushed with small amounts of water, usually taken from a container by means of a small receptacle. The resulting black water can be treated on-site or off-site. The strengths of this toilet type are the low water consumption of about 9 litre per capita per day and the relatively low cost. Disadvantages are the labour involved with filling the water containers and the need of providing a septic/interceptor tank for the separation of solids from black water. The latter is required as the low flush volume does not provide self-cleansing conditions in the sewer system. On-site discharge of septic-tank effluent from pour-flush toilets at a high groundwater table may require the use of drainfields instead of soakage pits. The system is widely used as a first step in the direction of individual household flush toilets. It presupposes a household connection to a water supply system.

6.2.1.4 Cistern-flush toilets

Cistern-flush toilets use a relatively large amount of water, stored in cistern (a small reservoir) to flush both urine and faeces. The large amount of flush water applied facilitates
the transport of faecal matter through sewer pipes. The strength of this system is its convenience and consequently the high degree of acceptance by its users. Weaknesses are the high consumption of flush water in the range of 40 l/cap.d and the strong dilution of the faecal matter which increases the costs of transport and treatment. In order to mitigate the disadvantages of full flush toilets, the use of *dual-flush cistern toilets* has now become widespread. The flush-water consumption of these dual flush toilets is estimated to be in the order of 28 l/cap.d. This flush volume is considered sufficient to transport faeces through the sewer pipes without blockages, so that no interceptor or septic tank for solids retention is needed. The black water from cistern-flush toilets can be treated off-site or on-site with a septic tank plus soakage pit. In the case of on-site treatment at a high groundwater table a drainfields instead of soakage pits may be required. Pour-flush and cistern-flush toilets are applied in the drainage and sanitation system groups 3, 4 and 6.

6.2.1.5 Urine-diverting flush toilets and urinals

The *urine-diverting flush toilet* (also called ‘no-mix’ toilet) can be used where flush toilets are technically feasible and affordable and a high priority is given to source separation of nutrients. The urine, which contains approximately 80% of the nitrogen and 40 – 50% of the phosphorous in domestic wastewater (chapter 5, table 5.2) is collected undiluted in a urine tank for transport, treatment and reuse, and the faeces is flushed to the sewer system (Gajurel et al., 2003; La Cour Jansen and Koldby, 2003; Wilsenach, 2006; Peter-Froehlich et al., 2007). The system is still in an experimental stage. One of the main problems can be the transport of urine, as it appears to cause clogging of transport pipes through scale formation (Larsen and Lienert, 2007). Complete separation of urine and brown water/faeces should not expected (see subsection 6.5.8). This toilet type is applied in the drainage and sanitation system groups 5, 7 and 12 (chapter 5, table 5.4). In addition to the use of urine-diverting flush toilets *urinals* can be applied. They are toilets for men, operated to collect urine separately. A distinction is made between low and no-flush urinals. In order to limit the costs of urine transport as little flush water as possible should be applied.

6.2.1.6 Vacuum toilets

The use of *vacuum toilets* implies the collection of black water (faeces, urine and flush water) by means of a vacuum pipe system (section 6.4) using very small amounts of flush water and the subsequent treatment to recover biogas and nutrients. The grey water is transported and treated separated. The present commercial vacuum toilets have a flush water use of about 6 l/cap.d, which delivers black water with COD and N concentrations of about 10 respectively 1.8 g/l. It is still too early to be certain about the most feasible treatment and reuse approach for this black water and the optimum scale of the system. A possible treatment option by means of UASB reactors followed by nitrogen removal and phosphate recovery is described in section 6.5. The separate handling of black and grey water system is under development in Germany and in The Netherlands (Otterpohl et al., 1997; Kujawa-Roeleveld et al., 2005; Zeeman et al., 2008). The system could have significant environmental advantages, but due to its still experimental and high-tech nature and its high investment costs, it is at this moment deemed unsuitable in developing countries. Vacuum toilets are applied in the drainage and sanitation system groups 9 and 11 (table 5.4).

The flush-water consumption of each of the proposed toilet types is summarized in table 6.2.2.

Table 6.2.2 Flush water consumption of 6 different toilet types

Toilet type	Water use for faeces (l/cap.d)	Water use for urine (l/cap.d)	Water use total (l/cap.d)
Dry Accumulating Anaerobic Digestion[18]	0.25	0.1	0.75
Urine-diverting dry toilet[19]	0	0	0
Pour-flush toilet	4	5	9
Cistern-flush toilet (dual flush)	8	20	28
Urine-diverting flush toilet[20]	6	0	6
Black water vacuum toilet[21]	1-1.5	5-7.5	6-9

[18] (Chaggu, 2004).
[19] (Winblad and Simpson-Hébert, 2004).
[20] (Swedenviro, 2001).
[21] (Swedenviro, 2001; Kujawa, 2005).

6.2.1.7 Communal toilets

In places where households lack space for individual toilets communal toilets can be provided instead. Here, communal facilities are mentioned with dry anaerobic toilets (group 1), urine-diverting dry toilets (group 2) and pour-flush toilets (group 3)(chapter 5).

6.2.2 Other household appliances

6.2.2.1 Kitchen sink and dishwashing machines

The households in the system overview in this book are equipped with a kitchen sink from where the water used during the preparation of food and dishwashing is discharged. If households are provided with a septic tank, the kitchen sink and the dishwashing machine should be connected to it in order to remove solids (e.g. food residues, grease and oil). In the systems of group 9 and 11 in which kitchen biowaste can be co-digested the kitchen sink is equipped with a garbage grinder.

6.2.2.2 Shower, bath, washing machine

Showers, baths, wash basins and laundry-washing machines produce grey water, which is significantly less polluted than the black water from the toilet (table 5.2). This grey water can be treated to satisfy discharge standards relatively easily, since it contains only small concentrations of nitrogen and phosphorus compounds. Separate grey water treatment is applied in the groups 10 and 12 and further detailed in subsection 6.5.7.

6.2.3 Selection of toilet technologies

The following table 6.2.3 could help in the selection of appropriate toilet technologies. It enables the assessment of the feasibility of the six described toilet types in a situation under study. The first column lists the restrictive factors, that could render the application of a toilet option unfeasible. In the case of toilet technologies and household appliances the restrictive factors are lack of space near and in the house, absence of piped water for toilet flushing, high groundwater table and risk of flooding.

Table 6.2.3 Screening matrix for the choice of toilet types.
(+ = feasible, - = not feasible, X = irrelevant, VIP = ventilated improved pit-latrine; DAAD = dry anaerobic accumulation digester, UD dry = urine-diverting dry toilet; PF = pour-flush toilet; CF = cistern-flush toilet; UD flush = urine-diverting flush toilet; VAC = vacuum toilet; Dry Comm. = dry communal sanitation facility)

Technology / Restrictive factor	VIP	DAAD	UD dry	PF	CF	UD flush	VAC	Dry Comm
Lack of space in the house	X	-	-	-	-	-	-	+
Lack of space near the house	-	-	-	+	+	+	+	+
Absence of piped water	+	+	+	-/+	-	-	-	+
Lack of water-absorbing additive	X	X	-	X	X	X	X	X
High groundwater table	-	+	+	+	+	+	+	+
Risk of flooding	-	+	+	+	+	+	+	+

Only in the case of dry communal systems with DAAD toilets or urine-diverting dry toilets none of the restrictive factors is applicable, meaning that they could be applied anywhere, supposing that a community can always find some space for communal sanitation facilities and that access for emptying vehicles can be assured.

The screening matrix shows that urine-diverting dry toilets (UD dry) for example are not feasible (-) where there is a lack of space near or in the house and where there is a lack of water-absorbing additives for the coverage of faecal matter. On the other hand this toilet type is feasible where there is an absence of piped water, since no water for toilet flushing is required. In contrast to the ventilated improved pit latrines (VIP), the other listed toilet options are feasible at high groundwater tables and risk of flooding, since they do not rely on discharge into the soil near the house.

6.2.4 Strengths, weaknesses and appropriate application of toilet technologies

The choice of a certain toilet option has consequences for the ensuing chain of collection, transport, treatment and reuse/disposal. The urine-diverting dry toilet for example presupposes on-site and separate collection, treatment and reuse of urine and faecal matter. These chains are all schematically shown in chapter 5 and are not detailed here.
In order to further inform the choice of toilets, their flush-water requirements, strengths and weaknesses are summarized in table 6.2.4. It can be concluded from this table that the sanitation systems that start with urine-diverting flush toilets and vacuum toilets are not appropriate where there is no institutional will to save water and recover and reuse the resources in wastewater.

Table 6.2.4 Strengths, weaknesses and conditions of most appropriate application of different toilet types.

	Ventilated improved pit latrine (VIP)	Dry accumulating anaerobic digestion toilet (DAAD)	Urine-diverting dry toilet (UD-dry)	Pour-flush toilet (PF)	Cistern-flush toilet (CF)	Urine-diverting flush toilet (UD-flush)	Vacuum toilet (VAC)
Indicative water consumption (l/cap.d)	0	0.75	0	9	28 (dual flush) 40 (single flush)	6	6 –9
Strengths	No use of flush water; easy to build	Small use of flush water; biogas production; reuse of slurry; reuse of biogas (in communal applications)	No use of flush water; hygienization of faecal matter through drying; reuse of urine and faeces; low costs	Low water use and limited costs	Convenience and broad user acceptance	Low water use; low emissions and reuse of nutrients through separate urine collection; reduced costs of central wastewater treatment	Convenience; low water use; high reuse potential (biogas and nutrients)
Weaknesses	Soil and groundwater pollution; risk of flooding; pit emptying is cumbersome	Expensive cartage of slurry; methane escape to atmosphere, if biogas is not captured	Need of additives for faecal matter dehydration; separate collection of urine and faeces	Labor of filling containers; need of interceptor/ septic tank before transport of black water	High water use; expensive where off-site treatment is required	Separate collection of urine; complete separation of urine and faeces not attainable in practice	Technically complex and expensive
Conditions of most appropriate application	Low-income areas with no piped water; lack of water for toilet flushing	No piped water supply; lack of water for toilet flushing	Low-income areas with no piped water; need of human excreta for fertilization of land	Piped water supply; importance of saving water	Piped water supply; no need of saving water	Need of saving water and energy and recovering resources from excreta	Need of saving water and energy and recovering resources from excreta; good institutional back-up

6.3 On-site wastewater storage and treatment options

6.3.1 Introduction to on-site treatment

The drainage and sanitation system options inventory of chapter 5 introduces two classes of on-site treatment. First, there are the systems with dry accumulating anaerobic digestion toilets (group 1), urine-diverting dry toilets (group 2) and flush toilets (group 3). In these systems a part of the excreta and wastewater treatment takes place on-site prior to disposal, while faecal sludge is transported for off-site treatment. Secondly, other off-site system groups include options with septic tanks for on-site solids removal and partial bio-degradation or on-site urine storage tanks. Table 6.3.1 gives an overview of the various on-site treatment technologies that are discussed in this chapter with the aim of enabling a performance comparison and estimating their contribution to the drainage and sanitation systems in their totality.

Table 6.3.1 On-site treatment technologies applied in the systems overview

On-site treatment technologies	Drainage and sanitation system group (see chapter 5)	Goal
Horizontal-flow septic tank Horizontal-flow septic tank with anaerobic filter UASB septic tank Baffled anaerobic septic tank Baffled anaerobic septic tank with anaerobic filter Imhoff tank	3 until 12	Solids and organic matter removal from sewage, black water and grey water applied in household on-site, and sewered systems
Accumulating anaerobic digester Anaerobic stirred tank reactor	9, 11	Organic matter conversion to biogas in black water, kitchen bio-wastes and other available organic wastes
Soakage pit Drain field	1, 2, 3	Household on-site effluent disposal
Urine tank	5, 7, 8, 10, 12	On-site urine storage

These technologies are discussed in the following subsections 6.3.2 until 6.3.7.
Constructed wetlands may be applied as an on-site treatment method as well. In this thesis this treatment method is discussed under the off-site treatment technologies (6.5.3).

6.3.2 Anaerobic primary treatment of wastewater

The primary wastewater-treatment technologies discussed here are the horizontal-flow septic tank (HFST) and the horizontal-flow septic tank followed by an anaerobic filter (HFSTAF) , the UASB septic tank (UASB-ST), the baffled anaerobic septic tank (BAST), the baffled anaerobic septic tank with anaerobic filter (BASTAF) and the Imhoff tank (IMH). The end products of anaerobic treatment are biogas, nutrient-rich sludge and effluent. The biogas production depends on the load, removal efficiency and biodegradability of the organic matter. The economically feasible utilization of biogas (about 38 l/cap.d maximum[22]) as a source of technical energy requires a certain minimum scale, since the heat value of biogas from human excreta under these conditions is only about 0.7 MJ/cap.d[23]. Where the gas can be used as a source of energy, it may be propitious to co-digest kitchen waste of other available bio-wastes for a higher energy production. Kitchen waste can be supplied to the digester, after shredding, jointly with wastewater or after collection as solid waste. Where the biogas is not captured, its emission to the atmosphere is a disadvantage, as the escaped methane contributes to global warming (Forster et al., 2007). After due treatment, septic-tank sludge could be utilized as a soil-conditioner in agriculture. This form of treatment is discussed in subsection 6.5.10. The effluent of anaerobic primary on-site treatment technologies is either disposed of on-site (in surface water or soil, possibly after post-treatment with a soakage pit or drain field) or further treated off-site after transport. A literature overview of the performance of various septic-tank types based on partial anaerobic treatment under various conditions is presented in table 6.3.2. A explanation of the technologies is given in the subsections below.

6.3.2.1 Horizontal-flow septic tank

On-site pre-treatment of sewage, black and brown water with horizontal-flow septic tanks (HFST) is applied in many of the drainage and sanitation system options presented in chapter 5. Grey water septic tanks mainly have the function to remove fats and grease discharged with kitchen wastewater. Septic tanks for source-separated black, brown or grey water could be made smaller than septic tanks for mixed black and grey water by virtue of a lower hydraulic and solids loading rate. On-site removal of solids and part of the dissolved organic matter enhances the lifetime and reliability of soakage pits used as a post-treatment step (Chapter 5, system groups 1, 2 and 3) and may allow a reduction of construction costs of sewers as less slope for self-cleansing is required and pipe diameters can be smaller (Chapter 5, system groups 6 and 7). Where there are no central wastewater-treatment plants the on-site septic tanks provide at least some degree of pollution reduction. An additional advantage of septic tanks is a lower need of maintenance and higher system reliability where water supply is limited or intermittent, which often occurs in low-income areas. In Vietnam septic tanks for on-site treatment are in place before a sewer system is laid out, and after construction of sewerage they discharge their effluent into the sewers. The treatment efficiencies in horizontal-flow septic tanks may vary considerably dependent on the type of septic tank (one, two or three compartments), characteristics of wastewater, retention time, temperature and state of maintenance. As no systematic data were found regarding horizontal-flow septic-tank treatment applied to separately collected black water, brown water or grey water, removal efficiencies and sludge generation rates for these types of wastewater had to be assumed.

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[22] The theoretical production of CH_4 from COD is 0.25 kg CH_4 per 1 kg COD. 0.25 kg CH_4 corresponds to 0.25/16 mol = 0.0156 mol, or 0.0156 * 22.4 m^3 at 273 °K = 0.35 m^3 CH_4 gas. The COD discharged with black and grey water is 0.109 kg/cap.d (see table 5.2), which corresponds to a maximum theoretical CH_4 production of 0.109 * 0.25 = 0.027 kg CH_4/cap.d with a heat value of 0.027 * 50.4 MJpe = 1.37 MJpe/cap.d. The CH_4 volume of 0.027 kg of CH_4 would be 0.027/16 * 22.4 = 0.0378 m^3. At 30% CO_2 the biogas volume would be 0.054 m^3. In practice only a part of the COD in wastewater can be converted to reusable methane. If 50% of the sewage influent COD (109 g/cap.d) is converted to reusable methane, the yield is about 0.014 kg CH_4/cap.d (De Graaff, 2010).

[23] The COD of human excreta is assumed to be 0.057 kg/cap.d (table 5.2), which corresponds to a maximum theoretical CH_4-production of 0.014 kg CH_4/cap.d with a heat value of 0.014 *50.4 = 0.70 MJpe/cap.d.

Table 6.3.2 Efficiencies of several types of on-site wastewater-treatment techniques.
(BW = black water; GW = grey water; KW = kitchen biowastes; LSW = livestock waste)

Type	Climate	Wastewater	HRT	COD_{tot}	BOD_5	TSS	References
				Treatment efficiencies			
			(days)	(%)			
HFST	temperate	BW + GW	4.6	45	46	18	(Viraraghavan T., 1976)
HFST	unspecified	BW + GW	5	60-70	n.a.	n.a.	(USEPA, 2002)
HFST	tropical	BW + GW	5.5	29	n.a.	29	(Mgana, 2003)
HFST	unspecified	unspecified	n.a.	47	27	70	(Polprasert and Rajput, 1982)
HFSTAF	tropical	BW + GW	67	99	n.a.	n.a.	(Raman and Chakladar, 1972)
UASB-ST	tropical	BW + GW	1.7	67-77	n.a.	81	(Bandung Study, 1991)
UASB-ST	tropical	BW	16	90-93	n.a.	93-97	(Bandung Study, 1991)
UASB-ST	10-33 °C	BW + GW	2	50	n.a.	n.a.	(Mahmoud, 2008)
UASB-ST	tropical	BW + GW	0.25	64	n.a.	n.a.	(Mgana, 2003)
UASB-ST	25 °C	BW	29	75-80	n.a.	n.a.	(Luostarinen et al., 2007)
UASB-ST	30 °C	GW	0.75	64	n.a.	n.a.	(Elmitwalli and Otterpohl, 2007)
BAST	tropical	BW + KW + LSW	2	88	88	94	(Viet et al., 2008)
BASTAF	tropical	BW	2	77	71	86	
IMH	tropical	BW + GW	0.6	25-50	25-35	n.a.	(Sasse, 1998)

According to the literature N and P removal in horizontal-flow septic tanks fluctuate between 0 and 25% respectively 0 – 20% (Alexandre and Boutin, 1998; Costa et al., 2002; USEPA, 2002; Mgana, 2003). Pathogen removal in septic tanks is low and usually less than one log unit (< 90%). Helminth-ova removal is brought about by sedimentation and removal of intestinal bacteria by sedimentation combined with natural die-off. An estimate of the methane generation from septic tanks is given in section 6.3.4. It has been assumed in this thesis, that septic tanks under the tropical conditions of Vietnam and HRT values of approximately 3 days attain an average COD_{tot}, N and P removal of 40, 3 and 7% respectively[24]. The treatment efficiency of a horizontal-flow septic tank can be enhanced by adding an anaerobic filter as a post-treatment step (HFSTAF) ((Raman and Chakladar, 1972; Polprasert and Rajput, 1982). Possible clogging of such a filter is mentioned as a disadvantage. Septic tanks may lead to groundwater pollution due to leakage caused by deficient construction and /or degradation in time. The sludge accumulation rate for septic

[24] Taking as input data an average septage production rate of 110 l/cap.yr ((Brandes, 1978; Strauss et al., 1997) with a TSS concentration of 30 g/l ((USEPA, 2002) and percentages of 4.6% N and 1.6% P in septage TSS, the annual septage accumulation rate is 3.3 kg TSS/cap.yr with 0.15 kg N_{tot}/cap.yr and 0.053 kg P_{tot}/cap.yr. Adopting total N_{tot} and P_{tot} loads to septic tanks of 4.93 kg N_{tot} and 0.73 kg P_{tot}/cap.yr (chapter 5), it can be calculated that the overall removal of N_{tot} and P_{tot} in septic tanks is equal to 3 respectively 7%.

tanks treating sewage is assumed to be 0.04 m^3/cap.yr (Mara, 1996b, p 77) and the flow of collected sludge (septage) is 0.11 m^3/cap.yr (Strauss et al., 1997). The difference between collected and produced excess sludge is due to the de-sludging practice in which collectors usually remove water in addition to sludge. Septic tank de-sludging frequency depends on the volume of the tank. A usual frequency is once in 4 years and the costs in Vietnam are 20 – 25 USD per tank of 2 m^3 emptied (year 2008)[25].

6.3.2.2 UASB septic tank without and with biogas utilization

UASB reactors can be used for household and community on-site treatment of mixed black/brown and grey water, black water from pour-flush toilets and vacuum toilets and for grey water. A UASB reactor for domestic sewage has a typical hydraulic retention time of 6 - 8 hrs, which is significantly lower than horizontal-flow septic tanks (HRT = 2 – 6 days). A UASB septic tank (UASB-ST) must have a longer hydraulic retention time than a UASB reactor, as this technology includes more storage space for sludge. The hydraulic retention time therefore depends on the required sludge-storage space, the sludge mass present, and consequently on the de-sludging frequency. An important difference between the UASB septic tank and the horizontal-flow septic tank is the upwards flow of the influent through the sludge bed and the presence of a gas-solids-liquid separator at the top of the tank. This separator enables the collection of the biogas and the retention of the sludge in the tank. The upflow regime facilitates a good contact between influent and sludge, so that in principle higher treatment efficiencies are obtained than in horizontal-flow septic tanks (table 6.3.2). In the Bandung Study (1991) in Indonesia a UASB septic tank having a volume of 0.86 m^3 fed with sewage (HRT = about 1.75 d) removed 67 – 77% of the influent COD_{tot}. A UASB septic tank fed with black water (HRT = 16 d) from pour-flush toilets attained a COD_{tot} removal of 90 – 93%. Mahmoud (2008) found mean COD_{tot} removal efficiencies from 50% in the cold season to 65% in the hot season (in Palestine) in a UASB septic tank fed with sewage at an HRT of 2 days.

The mass balance of an UASB septic tank (T = 25 ^oC, HRT = 29 d) fed with black water from regular flush toilets looked as follows: 20 - 25% of the incoming COD was discharged with the effluent (75 - 80% COD_{tot} removal), about 50% of the influent COD_{tot} was retained in the reactor as sludge, and 25 - 30% was converted to methane (Luostarinen et al., 2007). Luostarinen and co-workers (2007) showed that temperature has much influence on the biogas production, but much less on the COD_{tot} removal in UASB septic tanks. Throughout winter and summer in The Netherlands particulate COD from black water is removed with an efficiency of 60 – 90 %, while the dissolved and stored particulate COD are converted to biogas much more efficiently in summer than in winter. A second factor important to rapid attainment of the steady-state conversion efficiency is the quality of the seed sludge.

UASB septic tanks are particularly useful where the biogas can be utilized, e.g. in community on-site treatment plants. UASB septic tanks are still at a stage of development. Practical tests with different designs are strongly recommended. At an equal volume the UASB septic tank will be slightly more expensive that the horizontal-flow septic tank due to the need of a construction to collect and store biogas. If such device is not necessary and only upward flow is induced, the construction costs could be equal. The data on the treatment in UASB septic tanks of concentrated black water from vacuum toilets and grey water (table 6.3.4) are derived

[25] Personal communication with Mr Tran Van Thinh (2008).

from respectively Kujawa (2005) and Elmitwalli and co-workers (Elmitwalli and Otterpohl, 2007). Some elaboration of these data is given in subsection 6.5.6.

6.3.2.3 Baffled anaerobic septic tank

An improvement of the septic tank similar to the UASB septic tank is the baffled anaerobic septic tank (BAST). The principle which results in higher treatment efficiencies is an enhanced contact between influent and sludge, and plug flow. The tank comprises several compartments in series. The influent is introduced at the bottom of each compartment and flows to the outlet of the compartment in up-flow mode. Most COD conversion and sludge accumulation takes place in the first two compartments, while the subsequent compartments serve as additional settling tanks. The treatment efficiencies reported in table 6.3.2 are based on studies with a community-scale BAST receiving black water, kitchen waste, and live-stock breeding wastewater with an average influent COD_{tot} of about 2,500 mg/l (Viet et al., 2008). Another measure to improve the removal efficiency could be the addition of an anaerobic upflow filter to the BAST, thus resulting in the baffled anaerobic septic tank with anaerobic filter (BASTAF). The outcome of a field study with this system fed with black water is also shown in table 6.3.2. The COD_{tot} removal efficiencies of a community BAST and a household BASTAF at a design hydraulic retention time of 2 days were respectively 88 and 77% (Viet et al., 2008).

6.3.2.4 Imhoff tank

With respect to its function of solids removal and partial biodegradation the Imhoff tank is comparable to septic tanks, though its construction is different. The Imhoff tank has proven itself as a very reliable and flexible primary treatment technology used for communal wastewater-management systems, though rarely for individual households (Alexandre and Boutin, 1998; Sasse, 1998). The tank consists of one or two relatively small settling compartments on top of a large anaerobic sludge storage compartment. Its main function is suspended solids removal and digestion. The hydraulic retention time in the sedimentation compartment is about 2 hrs while the overall hydraulic retention time is about 14 hrs. The treatment efficiency is 25 – 35 % BOD and 25 – 50% COD_{tot} removal (Sasse, 1998, p 75). The sludge storage compartment has to be emptied from time to time and the sludge should be hygienized before disposal on land.

6.3.3 Treatment of excreta in anaerobic digesters

Excreta, the mixture of faeces, urine and anal cleansing water, is generated at the use of dry toilets (Chapter 5, group 1). The COD_{tot} concentration of a mixture of faeces and urine is about 50 g/l. Digesters are more appropriate for the treatment of excreta than septic tanks, since the liquid content of excreta is relatively low and separation between solids and liquid is hard to attain and moreover not useful where the resulting slurry is used as fertilizer. Accordingly, in digesters sludge and liquid are not separated, as opposed to septic tanks. In practice, often human excreta and animal manure are co-digested. The end products of the digestion are biogas and a slurry containing the unconverted organic matter and nutrients. After appropriate hygienization, the slurry can be used directly as organic fertilizer. Two types of anaerobic digesters are discussed here: the accumulating (AAD) and the continuous flow (ASTR) digesters. The AAD is proposed in on-site (drainage and sanitation system option 1A) and ASTR in communal systems (drainage and sanitation system option 1B) and the treatment of concentrated black water (drainage and sanitation system group 9 and 11).

6.3.3.1 Accumulating anaerobic digester

In accumulation (AAD) systems the influent is fed to the digester until it is full and is being treated simultaneously. After having reached its maximum volume or the required storage time, the AAD reactor is emptied, during which a part of its contents is retained to serve as seed sludge for the next run. Biogas can be captured for utilization, though this will be feasible only above a certain system size. Accumulation systems are particularly useful for highly concentrated wastestreams, like excreta and kitchen waste, in situations where the resulting product is carted off intermittently, and a period of storage, e.g. for pathogen die-off, is required. An important advantage of the accumulation reactor is its technical reliability. The size of accumulation reactors is determined by flow and storage time. Experimental data are presented in table 6.3.3 and 6.3.4. The production of methane from human excreta is estimated at 6.4 g CH_4/cap.d (26 g CH_4-COD/cap.d) (subsection 6.3.4). The flow of product slurry from a household system fed with faeces, urine and anal cleansing water, as proposed in system option 1A, would amount to 0.77 m^3/cap.yr (= 365 * 2.1 l/cap.d) (Chaggu, 2004, p 64). The faecal coliform removal efficiency is relatively high by virtue of the long retention time between start-up and tank emptying.

6.3.3.2 The anaerobic stirred tank reactor

A very common reactor system used in anaerobic treatment is the so-called completely stirred tank reactor (CSTR). This type or reactor applied to anaerobic treatment is named here anaerobic stirred tank reactor (ASTR). The ASTR is a continuous flow system without separation of solids and water. The stirring does not necessarily require a mechanical device, but can be brought about by the formed biogas. The dimensions of an ASTR used for treatment of excreta and concentrated black water are governed by the influent flow rate and the required hydraulic retention time, which is highly dependent on the reactor temperature. In the mesophilic temperature range (30 – 35 ^oC) the required hydraulic and sludge retention time is in the range of 20 – 30 days. Under these conditions a COD removal efficiency through conversion to methane of 55% may be expected. At lower temperatures much longer retention times are required for a comparable COD conversion. The removal of pathogenic organisms depends on the process temperature. Slurries processed at ambient and mesophilic temperatures are usually not safe for immediate reuse. The data presented in table 6.3.4 are derived from a model study on a mixture of concentrated black water and kitchen waste (COD_{tot} concentration = 29.1 g/l) by Zeeman and co-workers (2001). In the presented example the product slurry load is 1.90 m^3/cap.yr at an influent flow rate of 5.2 l/cap.d. The ASTR is widely used for the treatment of primary and secondary sewage-treatment sludges under all climatic conditions (see also subsection 6.5.9.1) and under tropical conditions for highly biodegradable slurries, such as human and animal excreta, without technical heating of the tank.

6.3.4 Methane generation in anaerobic pre-treatment

As methane production and emission to the atmosphere are important factors in the assessment of the performance of technologies, the methane generation of the different anaerobic technologies is estimated in this subsection (table 6.3.3). For anaerobic reactors for wastewater treatment the COD balance can be represented by the equation:

$$COD_{inf} = COD_{eff} + COD_{gas} + COD_{sludge} + COD_{sulph\ red} + COD_{unaccounted} \quad (6.1)$$

Here, the terms represent respectively COD in the influent, COD in effluent, CH_4-COD formed as gas, COD remaining in the reactor as sludge, COD converted at sulphate reduction and possible unaccounted COD losses, all expressed as a load (e.g.: g COD/cap.d) (Seghezzo, 2004, p 93). If we may neglect COD consumed at sulphate reduction and unaccounted for COD, the total methane gas production can be written as:

$$COD_{gas} = COD_{inf} * E_{COD} * B \quad (6.2)$$

Here, E_{COD} is the COD removal efficiency $((COD_{inf} - COD_{eff}) / COD_{inf})$ and
B the methanation factor or fraction of removed COD converted to CH_4.

Depending on the technology the formed methane gas (COD_{gas}) is emitted to the atmosphere (COD_{atm}) or partially captured for utilization ($COD_{gas\ captured}$):

$$COD_{gas} = COD_{inf} * E_{COD} * B = COD_{gas\ captured} + COD_{atm} \quad (6.3)$$

Further a loss factor (c_{loss}) for various types of anaerobic technologies may be defined as:

$$COD_{atm} = c_{loss} * COD_{gas} \quad (6.4)$$

For reactors, in which all methane, not dissolved in the effluent, is captured, can be written:

$$COD_{atm} = COD_{diss} = Q * c_{sol\ CH4} \quad (6.5)$$

in which Q refers to the per capita flow rate (l/cap.d), $c_{sol\ CH4}$ is the solubility of methane gas at the prevailing conditions (g CH_4-COD/l), and c_{loss} indicates the fraction of generated gas (COD_{gas}) lost to the atmosphere.
It may be assumed that the methane load dissolved in the effluent (COD_{diss}) is emitted, as soon as the effluent is exposed to the atmosphere. Accordingly, in reactors *with* gas capture $COD_{diss} = COD_{atm}$. In reactor types *without* gas capture $COD_{atm} = COD_{gas}$. In this case c_{loss} = 1.

In the calculations presented in table 6.3.3 the values of the influent COD loads (COD_{inf}) are indicative values derived from table 5.2 in chapter 5. Here, the COD load of sewage of 109 g COD/cap.d. Complete conversion to methane (E_{COD} and B = 1.0) would yield 109 g CH_4-COD or 27.2 g CH_4/cap.d. The methane production in primary treatment reactors is much lower than the ‘complete conversion value’, due to only partial removal and conversion of the supplied COD (E and B < 1.0). The values of E_{COD} and B depend on hydraulic and sludge retention time, the biological degradability of the influent COD, the temperature and other conditions.
The methanation factor B is related but not equal to the maximum anaerobic degradability, as in reactors in practice no complete degradation is achieved. The reported maximum anaerobic degradability of COD fractions in sewage is 72% and in grey water 76% (Elmitwalli and Otterpohl, 2007). The loss of methane via the effluent (COD_{diss}) can be calculated taking into account the solubility of methane gas in water at the temperature of the reactor and the composition of the biogas. The higher the influent COD concentration the lower the fraction of generated methane that leaves the reactor via the effluent. The COD_{diss} is approximately

16% of the COD_{inf} in UASB reactors fed with sewage with an influent COD_{tot} of 400 mg/l (T = 25 ^oC; 75% methane in generated biogas). In reactors fed with excreta (COD_{inf} = 10 g/l) under the same conditions only 0.7% of the COD_{inf} is lost as dissolved methane in the effluent. In table 6.3.3 the methane generation rates and emitted methane rates of horizontal flow septic tanks, UASB septic tanks, baffled anaerobic septic tanks, Imhoff tanks, anaerobic accumulating digesters and anaerobic stirred tank reactors are estimated in order to be able to rank the technologies with respect to their emissions of methane to the atmosphere.

6.3.4.1 Methane generation in horizontal flow septic tanks

In horizontal-flow septic tanks the produced methane is not captured and consequently emitted to the atmosphere. The factor c_{loss} = 1.0. The average COD removal efficiencies (E) and the fraction converted (B) for tropical conditions and all concerned types of wastewater are tentatively estimated at 0.4 and 0.7 respectively. Thus, the methane generation rate from sewage under these circumstances is 109 * 0.4 * 0.7 = 30.5 g CH_4 –COD/cap.d, and 30.5 * 0.25 = 7.6 g CH_4/cap.d. Recent studies on a UASB-septic tank run at 30^o C and fed with grey water showed that 76 - 80% of the removed COD was converted to methane (B = 0.8) (Elmitwalli and Otterpohl, 2007). It should be noted that few data were found regarding the methanation factor (B) in septic tanks, so that more research seems to be needed in this domain. For the horizontal-flow septic tank followed by an anaerobic filter (HFSTAF) an average COD_{tot} removal efficiency (E) of 60% and a methanation factor (B) of 0.7 were assumed. The latter is equal to the value for regular septic tanks.

6.3.4.2 Methane generation in UASB septic tanks and baffled anaerobic septic tanks

The data presented about the methane generation in UASB septic tanks are based on the following references. Data about sewage and black water come from experiments carried out under tropical conditions in Indonesia (Bandung Study, 1991), data on black water and concentrated black water from De Graaff (2010), Luostarinen and co-workers (2007) and Kujawa (Kujawa, 2005), and data on the treatment of grey water from Elmitwalli and Otterpohl (Elmitwalli and Otterpohl, 2007).

In the research of the Bandung Study a UASB-septic tank (0.80 m^3) was fed with an average *sewage* flow of 489 l/d having an average COD_{tot}-concentration of 1.36 g/l. Having measured an average biogas production of 180 l/d with a methane concentration of 78%, the captured methane generation rate was 140 l/d (91 g CH_4/d or 364 g CH_4-COD/d). The dissolved CH_4-COD leaving the tank with the effluent is calculated to be 7.3 g CH_4/d (29 g CH_4-COD/d). Accordingly, the total amount of methane generated was 98 g CH_4/d. (393 g CH_4-COD/d). As the tank served 9 persons the methane production was 10.9 g CH_4/cap.d (44 g CH_4-COD/d) (Bandung Studies, 1991).

A UASB-septic tank fed with *black water* from pour-flush toilets used by 9 persons in the Bandung Study (flow: 54 l/d; influent load: 297 g/d COD_{tot}) produced on average 118 l/d of biogas at a methane concentration of 84.5%. This implies a captured methane production of 64.6 g CH_4/d (258 g CH_4-COD/d). The dissolved methane is estimated at 0.90 g CH_4/d. The total methane generation therefore amounted to 65.6 g CH_4/d or 7.3 g CH_4/cap.d (29 g CH_4-COD/cap.d) (Bandung Study, 1991). From the above figures the following values of the fraction of COD removed converted to methane (B) were derived. The values of B were 0.71 in the case of the treatment of sewage and 0.97 in the case of black water. The latter figure would mean that nearly all removed COD was converted. Despite the long sludge retention time in the tank such a high conversion is not likely.

Table 6.3.3 Indicative values of methane generation and emission to the atmosphere in anaerobic pre-treatment systems fed with different types of wastewater under tropical conditions

(S = sewage (= BW + GW), BW = black water, BrW + GW = Brown + grey water, GW = grey water, KW = kitchen waste)

Technology	Wastewater type	Influent load	COD removed (E_{COD})	Removed COD converted to CH_4 (B)	Methane generation	C_{loss}	Methane emitted to atmosphere (COD_{atm})
		g COD/ cap.d	Fraction	Fraction	g CH_4-COD/ cap.d	Fraction	g CH_4-COD/ cap.d
HFST	S	109	0.4	0.7	30	1.0	30
	BW	57	0.4	0.7	16	1.0	16
	BrW + GW	97	0.4	0.7	27	1.0	27
	GW	52	0.4	0.7	15	1.0	15
HFSTAF	BW	57	0.6	0.7	24	1.0	24
UASB-ST	S	109	0.75	0.7	57	1.0	57
	BW	57	0.75	0.7	30	1.0	30
	Conc. BW	57	0.75	0.7	30	~ 0	~ 0
	GW	52	0.6	0.8	25	1.0	25
BAST	BW	57	0.75	0.7	30	1.0	30
IMH	S	109	0.3	0.7	23	1.0	23
AAD	Excreta	57	1.0	0.45	26	0	~ 0
	BrW + KW	125	1.0	0.55	69	0	~ 0
ASTR	BW + KW	152	0.55	1.0	84	0	~ 0

Luostarinen and co-workers (2007) found values of E_{COD} and B of 0.70 and 0.29 respectively in the UASB septic tank treatment of *black water* from cistern-flush toilets at temperatures between 14 and 19 ^oC. Here, the values of E_{COD} and B for black-water treatment in the tropics were tentatively assumed to be 0.75 and 0.7 respectively (table 6.3.3).

For the treatment of *concentrated black water* originating from vacuum toilets in UASB-septic tanks (HRT = 29 d, T = 25^o C) values for E_{COD} and B of respectively 0.75 and 0.3 were found (Kujawa, 2005, chapter 5; Luostarinen et al., 2007). De Graaff (2010, p 47) reported that a UASB reactor operated at 25 ^oC removed on average 73% (E_{COD} = 0.73) of the incoming COD_{tot} from concentrated black water, while 54% of the same COD_{tot} was recovered as methane. This leads to a methanation factor B equal to 0.74. It is assumed here that the values of the methanation factor found by Luostarinen and co-workers and Kujawa were low due to methane losses. In this thesis for *concentrated* black water the same values for E_{COD} and B as for black water were assumed, namely 0.75 and 0.7 respectively. As biogas from UASB septic tanks fed with concentrated black water will usually be captured for utilization, only the methane dissolved in effluent is lost. Under the circumstances of the reactors run by Kujawa this loss is about 0.5% of the influent COD load, so that this loss can be neglected.

In the case of anaerobic *grey water* treatment a methanation factor (B) of COD removed equal to 0.8 (HRT = 16 hrs, T = 30 ^oC) was reported (Elmitwalli and Otterpohl, 2007). The COD removal efficiency (E_{COD}) in black water treated by a baffled anaerobic septic tank (BAST) amounts to approximately 75% (Viet et al., 2008). As no methanation data were found for this type of septic tank in literature, the same value of B as for the UASB septic tank (0.7) has been assumed.

6.3.4.3 Methane generation in anaerobic accumulating digesters (AAD) and stirred tank reactors (ASTR)

In an accumulating anaerobic digester (AAD) system there is no effluent, so that the input remains in the reactor until the reactor is full. Therefore the value of the removal efficiency E_{COD} is per definition equal to 1.0. For an AAD fed with concentrated brown water and kitchen refuse (average influent COD_{tot} = 53.6 g/l, flow: 2.6 l/cap.d), operated at 20^{o} C, a methanation rate of 51% was reported, and an AAD system fed with black water and kitchen refuse showed a similar digestion rate (Kujawa, 2005, p 41). Here, it is assumed that in tropical AAD systems connected to dry toilets 45% of the stored COD is converted to methane (B = 0.45) and accordingly the methane generation is in the order of 26 g CH_4-COD/cap.d. The ASTR is a flow-through system without separation of liquid and solids (sludge). Accordingly, the COD removed is equal to the COD converted to methane and the value of the methanation factor is per definition equal to 1.0. The methane losses due to dissolved methane in the final digestate (effluent) can be neglected, as they are very small in comparison to the influent and the captured gas loads.

6.3.5 Conclusions about anaerobic primary treatment technologies

In order to be able to compare anaerobic primary technologies for the treatment of various types of wastewater the data with regard to design and performance parameters collected in this section are summarized in table 6.3.4. The most important data for comparison of the pre-treatment options are hydraulic retention time (HRT) and specific tank volume (impact on construction costs), the COD removal efficiency, the methane generation and the sludge volume collected (impact on operational costs). Comparison of the specific installed tank volumes (m^3/cap) and COD - removal efficiencies shows that UASB septic tanks can be built considerably smaller and have higher efficiencies than horizontal-flow septic tanks. For treatment of sewage the specific reactor volume of a horizontal-flow septic tank is the order of 0.3 m^3/cap (COD removal equal to 40%), for a UASB septic tank about 0.06 m^3/cap (COD removal equal to 67 – 77%) and an Imhoff tank 0.09 m^3/cap (COD removal about 30%). For the treatment of concentrated black water and black water plus kitchen refuse with a COD concentration in the range of 10 – 50 g/l, the UASB septic tank is the preferred system. This technology is used in drainage and sanitation system groups 9 and 11 (chapter 5) where black water is separately collected by means of a vacuum toilet/transport system. By virtue of a higher COD removal efficiency UASB septic tanks generate more CH_4 gas than horizontal flow septic tanks. In communities where the wastewater is treated in collective treatment units it may be cost-effective to utilize the biogas as a source of power and heat. The sludge volume collected depends on the quality of the wastewater treated and the sludge retention time in the tank. As UASB septic tanks convert more COD to biogas than horizontal flow septic tanks, it is to be expected that the former have a lower sludge generation rate. The accumulating anaerobic digesters (AAD) and anaerobic stirred tank reactors (ASTR) do not have separation between effluent and sludge, so that the hydraulic retention time is equal to the sludge retention time. This implies a relatively long hydraulic retention time and relatively big reactor volumes. Accordingly, AAD and ASTR technologies are most suitable for treatment of small volumes of concentrated slurries, like excreta, animal manure and kitchen biowastes.

6.3.6 On-site discharge to the soil: soakage pits and drain fields

Filtration technologies can play an important role in small-sale on-site treatment of wastewater, especially as an additional step after anaerobic pre-treatment. Here, a brief review is presented of soakage pits and drain fields.

Soakage (seepage/adsorption) pits and drain fields ((leach fields, absorption beds and trenches) are used for the discharge to the soil of various types of raw and pre-treated types of domestic wastewater (Polprasert and Rajput, 1982, p 52; Mara, 1996b, p 63, p 83). The soakage pit or trench is dug out in the soil, lined with stones or bricks and filled with stones and gravel for additional solids and organic matter retention and conversion. The soakage pits have a depth of at least 1.5 meter and should not reach the groundwater. Trenches can be shallower. The land use of soakage pits and trenches per unit of flow (m^3/d) depends on quality of the wastewater, the type of soil and the depth. Good long-term performance of soakage pits and trenches requires a permeable soil and prevention of organic and hydraulic overloading. Usual soil infiltration and BOD_5 loading rates are in the range of 10 (clay) – 50 l/m^2.day (sand) and 5 – 30 g BOD_5/m^2.d. For low-strength wastewaters the hydraulic loading rate is usually the critical parameter. Soakage pits for the relatively small flow of high-strength black water from pour-flush toilets are dimensioned using a design infiltration rate of 10 l/m^2.d. Clogging of soakage pits may occur even under controlled loading conditions so that provisions be made to clean the pit every 5 to 10 years (Polprasert and Rajput, 1982, p 57; PHSSDA, 2007, p 62; Tilley et al., 2008, p 137). Drain fields are applied where the permeability of the soil is relatively low. They take more land than soakage pits. In drain fields it is important to create a maximum vertical infiltration surface on a minimum area of land. Often against prevailing regulations ‘septic tanks’ are constructed without lined bottom, so that wastewater percolates into the subsoil. These ‘septic tanks’ are in fact soakage pits. The following indicative area requirements can be taken into account for the land use of combinations of septic tanks with soakage pits in warm climates: for pre-treated combined black and grey water (0.133 m^3/cap.d) : 0.8 m^2/capita[26]; for black water (0.043 m^3/cap.d): 0.3 m^2/cap and for source-separated grey water (0.09 m^3/cap.d): 0.4 m^2/cap. The discharge of wastewater to soakage pits and drain fields is capable of causing unacceptable soil and groundwater pollution especially at high building densities.

6.3.7 Storage of urine

Urine obtained as a separate source stream usually has to be stored on-site before transport, treatment and utilization. The required tank volume depends on the number of persons connected and the storage time. Urine storage is discussed in more detail in subsection 6.5.8.

[26] In this calculation the surface attributed to the septic tank is 0.27 m^2/cap and to the soakage pit 0.55 m^2/cap (See appendix 6.1).

Table 6.3.4 Treatment characteristics of anaerobic primary treatment techniques for different waste streams at temperatures > 20^{o} C[27].

Parameter	Unit	Horizontal-flow septic tank Sewage	Black water	Brown water + grey water	Grey water	UASB septic tank Sewage[28]	Black water[29]	Conc. black water[30]	Grey water[31]	IMH Sewage	AAD Excreta[32]	Conc. brown water + kitchen refuse[33]	ASTR Black water + kitchen refuse[34]
Toilet type	-	CF	CF	UD flush	-	PF	PF	VAC	-	CF	Dry	VAC	VAC
Temperature	^{o}C	*20 – 30*	*20 - 30*	*20 – 30*	*20 –30*	> 25	> 25	25	30	*20*	>25	20	30
Influent flow	l/cap.d	*100*	*40*	*66*	*60*	54	6	6.8	60	*100*	2.1	2.6	5.21
COD influent	g/l	*1.09*	*1.42*	*1.47*	*0.87*	1.36	5.54	12.3	0.64	*1.09*	27	53.6	29.1
COD load[8] rate	g/cap.d	*109*	*57*	*97*	*52*	74	33	84	38	*109*	57	139	152
HRT	days	*3*	*3*	*3*	*1.5*	1.6	16	29	0.75	*0.6*	143	115	20
Spec. tank vol.	m^3/cap	*0.3*	*0.12*	*0.2*	*0.09*	0.09	0.09	0.17	0.045	*0.09*	0.3	0.26	0.104
Effective depth	m	*0.8-1.5*	*0.7-1.5*	*0.8-1.5*	*0.7-1.5*	1.5-2.0	1.5-2.0	1.5-2.0	1.5-2.0	*2.5-5.0*	1.0-2.0	1.0-2.0	1.5-2.0
Land use[35]	m^2/cap	*0.2-0.38*	*0.08-0.17*	*0.13-0.25*	*0.06-0.13*	0.03-0.04	0.05-0.07	0.08-0.11	0.02-0.03	*0.02-0.04*	0.15-0.30	0.13-0.26	0.05-0.07
COD loading rate	kg/m^3.d	*0.36*	*0.47*	*0.49*	*0.58*	0.83	0.34	0.42	0.85	*1.2*	n.a.	n.a.	1.46

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[27] Figures in this table printed in *italics* refer to technical design literature. Figures printed in normal font refer to a journal article or research report.

[28] (Bandung Study, 1991, chapter 5): Sewage: the average flow was 489 l/d for 2 households with 9 persons, which results in an average per capita flow of 54 l/d.

[29] (Bandung Study, 1991, chapter 3): Black water: the average flow-rate was 53 ± 19 l/d from 2 households with 9 persons. The effective UASB-ST volume was 0.80 m^3. The biogas production amounted to 13.1 l/cap.d with a methane fraction of 0.845. Sewage: the average flow was 860 l/d from 11 persons.

[30] (Kujawa-Roeleveld et al., 2005; Kujawa, 2005, chapter 5; Kujawa-Roeleveld et al., 2006).

[31] (Elmitwalli and Otterpohl, 2007).

[32] (Chaggu, 2004, chapter 5).

[33] (Kujawa, 2005, chapter 4 experiment AC2, run 2). Both concentrated brown water and kitchen waste were flushed into the AAD. In a mixture of excreta and kitchen waste after unfed anaerobic storage period of 142 days an E.coli removal of 99.993% was found. Accordingly a first order E.coli die-off constant of 0.067 d^{-1} (at 20^{o}C) was calculated.

[34] (Kujawa, 2005, chapter 4).

[35] Net area occupied by the technology. Often primary treatment systems are constructed under buildings and do not occupy land.

Table 6.3.4 (continued) Treatment characteristics of anaerobic primary treatment techniques for different waste streams at temperatures > 20^{o} C[36].

Parameter	Unit	Horizontal-flow septic tank				UASB septic tank				IMH	AAD		ASTR
		Sewage	Black water	Brown water + grey water	Grey water	Sewage[37]	Black water[38]	Conc. black water[39]	Grey water[40]	Sewage	Excreta[41]	Conc. brown water + kitchen refuse[42]	Black water + kitchen refuse[43]
COD rem. eff.	%	*40*	*40*	*40*	*40*	67 – 77	90 – 93	78	64	*30*	n.a.	51	55
N_{tot} rem. eff.	%	*0*	*0*	*0*	*0*	low	low	low	low	*low*	0	0	0
P_{tot} rem. eff.	%	*0*	*0*	*0*	*0*	low	low	low	low	*low*	0	0	0
FC rem. eff.	%	*90*	*90*	*90*	*<90*	n.a.	low	n.a.	n.a.	*low*	n.a.	High	Low
Methane gen.[44]	g CH_4/cap.d	*7.6*	*4.0*	*6.8*	*3.8*	8.9-11.6	7.3	4.6[45]	4.9	*5.8*	n.a.	17.8	20.8
Sludge accum.	m^3/cap/yr	*0.04*	*0.02*	*n.a*	*n.a.*	n.a	n.a.	0.023	n.a.	*n.a.*	0.77	0.84	1.90
Sludge volume collected	m^3/cap/yr	*0.11*	*n.a*	*n.a*	*n.a.*	n.a	n.a.	n.a.	n.a.	*n.a.*	0.77	0.84	1.90

[36] Figures in this table printed in *italics* refer to technical design literature. Figures printed in normal font refer to a journal article or research report.
[37] (Bandung Study, 1991, chapter 5): Sewage: the average flow was 489 l/d for 2 households with 9 persons, which results in an average per capita flow of 54 l/d.
[38] (Bandung Study, 1991, chapter 3): Black water: the average flow-rate was 53 $\pm$ 19 l/d from 2 households with 9 persons. The effective UASB-ST volume was 0.80 m^3. The biogas production amounted to 13.1 l/cap.d with a methane fraction of 0.845. Sewage: the average flow was 860 l/d from 11 persons.
[39] (Kujawa-Roeleveld et al., 2005; Kujawa, 2005, chapter 5; Kujawa-Roeleveld et al., 2006).
[40] (Elmitwalli and Otterpohl, 2007).
[41] (Chaggu, 2004, chapter 5).
[42] (Kujawa, 2005, chapter 4 experiment AC2, run 2). Both concentrated brown water and kitchen waste were flushed into the AAD. In a mixture of excreta and kitchen waste after an unfed anaerobic storage period of 142 days an E.coli removal of 99.993% was found. Accordingly, a first order E.coli die-off constant of 0.067 d^{-1} (at 20^{o}C) was calculated.
[43] (Kujawa, 2005, chapter 4).
[44] See table 6.3.3. Methane generated expressed as g CH_4-COD/cap.d is divided by a factor 4 to obtain the value of the methane generation in g CH_4/cap.d.
[45] Kujawa(2005) found that on average 22% of the concentrated black-water influent COD (84 g/cap/d), equal to 18.5 g CH_4-COD/cap.d or 4.6 g CH_4/cap.d, was converted to (measured) CH_4. The COD balance however showed a considerable gap of unaccounted COD of which probably a considerable part was produced but unmeasured CH_4.

6.3.8 Selection of on-site technologies

This section summarizes the results of section 6.3 by presenting the screening matrix and the overview of strengths, weaknesses and conditions of appropriate application of the discussed on-site storage and treatment technologies.

Table 6.3.5 could help stakeholders in drainage and sanitation planning in choosing between feasible and unfeasible on-site treatment technologies. The first column lists the restrictive factors that could make the application of the technology unfeasible. In the case of on-site technologies the restrictive factors are: absence of piped water, ambient temperature, the need of provision to individual households, absence of space for natural treatment methods, high solids concentration in the wastewater to be treated and lack of access to de-sludging vehicles. The table shows for example that a horizontal-flow septic tank is unfeasible where there is an absence of piped water and streets are too narrow for the access of de-sludging vehicles.

6.3.9 Strengths, weaknesses and appropriate application of on-site technologies

For comparison of primary anaerobic treatment technologies that can be used for treatment prior to on-site discharge or to further transport of wastewater the strengths, weaknesses and conditions of most appropriate application are summarized in table 6.3.6. This table reflects the following considerations:

Septic tanks (HFST, HFSTAF, UASB-ST, BAST and BASTAF) can be applied for treatment of black, brown and grey water. UASB-septic tanks and baffled septic tanks (BAST) have a much higher COD removal efficiency than the horizontal-flow septic tanks (HFST). This would be especially advantageous in systems with on-site reuse or disposal of effluent (Chapter 5, drainage and sanitation system group 1, 2 and 3). The land use associated with on-site disposal in soakage pits has been mentioned in subsection 6.3.6. with regard to soakage pits and drain fields.

Accumulating and stirred anaerobic digesters (AAD and ASTR) are suitable technologies for treatment of excreta from dry toilets, a condition related to the absence of piped water (drainage and sanitation system group 1). These digester types may also be applied for the treatment of concentrated brown water and black water and resulting from urine-diverting flush toilets and vacuum toilets (drainage and sanitation system group 5, 7, 9, 11, 12).

Utilization of biogas for energy generation requires ambient temperatures of at least 20 ^{o}C, since methane formation from organic matter decreases at lower temperatures. Where the wastewater streams are highly concentrated heating of digesters with the produced biogas to the required temperature may be economically feasible.

Where biogas is not utilized methane is emitted to the atmosphere and contributing to global warming. These emissions are stronger as COD removal is more efficient. Therefore the methane emissions from UASB septic tanks and BAST are higher than those from horizontal-flow septic tanks.

Utilization of biogas from sewage-fed individual-household UASB-septic tanks does not seem feasible, as the modest gas yield does not justify the required storage and utilization equipment. The situation is different for clustered households and public-commercial buildings, and where animal manure is the main substrate.

Table 6.3.5 Screening matrix for on-site wastewater storage, treatment and discharge technologies.
(+ = feasible; - = unfeasible; -/+ = feasible under certain conditions; X = factor not applicable)

Technology / Restrictive factor	HFST Without biogas utilization	HFST (-AF) Without biogas utilization	UASB-ST Without biogas utilization	UASB-ST With biogas utilization	BAST Without biogas utilization	IMH Without biogas utilization	AAD With biogas utilization	ASTR With biogas utilization	Soakage pit	Drain field	Urine tank
Absence of piped water	-	-	-	-	-	-	+	+	-	-	+
Ambient temperature < 20^{o} C	+	+	+	-	+	+	-	-	+	+	+
Application at individual households	+	+	+	-	+	-	-/+[46]	-/+[47]	+	+	+
Absence of space for natural treatment methods	+[48]	+	+	+	+	+	+	+	-/+[49]	-	+
Influent with high SS and COD concentration	+	+	+	+	+	+	+	+	-	-	X
Lack of access for de-sludging vehicles	-	-	-	-	-	-	-	-	X	X	X

[46] Biogas may be utilized in farming households where animal manure is available for digestion.
[47] See footnote above.
[48] Septic tanks require no extra space near houses, as they can be constructed in the basement under houses.
[49] Soakage pits need less space than drain fields, but different from septic tanks and anaerobic digesters they require space near the house.

Table 6.3.6 Strengths, weaknesses and conditions of most appropriate application of anaerobic primary wastewater and excreta treatment technologies at temperatures higher than 20^{o}C.

	HFST	HFSTAF	UASB-ST	BAST	IMH	AAD	ASTR
Strengths	Robust; simple construction	Improved treatment efficiency	High COD treatment efficiency; Biogas utilization	Robust; high COD treatment efficiency	Very robust; Low cost	Robust; possibility of biogas utilization	Robust; biogas utilization
Weaknesses	Low treatment efficiency; no utilization of biogas and emission of methane gas to atmosphere	No utilization of biogas and emission of methane gas to atmosphere; possible clogging of anaerobic filter (AF)	Little experience with construction and operation	No utilization of biogas and emission of methane gas to atmosphere	Relatively low treatment efficiency; no utilization of biogas and emission of methane gas to atmosphere	Transport of accumulated excreta could be expensive	Transport of slurry could be expensive
Conditions of most appropriate application	Combination with flush toilets; small-bore and shallow sewerage; high solids and a moderate COD removal from all types of diluted wastewater	Combination with flush toilets; absence of further treatment prior to disposal; high solids and moderate COD removal from all types of diluted wastewater	Combination with regular, urine-diverting flush toilets and vacuum toilets; high solids and COD removal from all types of wastewater; (sub-) tropical climates; need of biogas utilization	Combination with flush toilets; small-bore and shallow sewerage; high solids and COD removal from all types of diluted wastewater	Combination with flush toilets; communal pre-treatment; moderate solids and low degree of COD removal from all types of diluted wastewater	Combination with dry and vacuum toilets; need of storage and treatment of excreta and other bio-wastes prior to transport; possibility of biogas utilization	Combination with dry and vacuum toilets; need of concentrated black water treatment; availability of bio-wastes for co-digestion; immediate reuse of product slurry; possibility of biogas utilization

6.4 Transport of wastewater in off-site systems

6.4.1 Introduction

Transport systems carry wastewater and sludge streams from the households and their surroundings to the site of off-site treatment. In this section an overview is given of the technical and environmental characteristics of wastewater-related transport systems. Transport concerns the following waste streams: urine (yellow water), faeces with flush water (brown water), black water, grey water and stormwater and, if on-site treatment is used, also faecal sludge and faecal matter. It should be noted that urban areas have two stormwater drainage systems: one is the minor system which is the drainage system laid out to convey runoff under the conditions for which it has been designed and the other the major system which comes into action when the minor system's capacity is exceeded (Kolsky, 1998, p 19). The major system consists of street surfaces and natural watercourses. The transport options for wastewater applied here are:

- combined and settled combined sewer system (1 stream – 1 pipe);
- separate and settled separate sewer system (2 streams – 2 pipes);
- source-separated sewer system (3 streams – 3 pipes).

Systems that convey sewage and stormwater either combined (1 pipe) or separate (2 pipes) are common in many parts of the world. These sewer systems are associated with high building and population densities, the use of conventional flush toilets and a high water consumption. Due to the high costs of pipe networks, it is assumed here, that where black water, grey water or urine are collected separately the required third and fourth pipe network serve a small area. Urine transport lines are confined to high-rise buildings or serve a relatively small number of houses that share a treatment or storage system. Accordingly, there are no 4-pipe systems in the system options inventory in this thesis: urine is always transported by cartage. The transport systems summarized in table 6.4.1 cover the transport in the 12 drainage and sanitation system groups defined in chapter 5.

Table 6.4.1 Wastewater-related transport technologies discussed in this thesis.

Subsection of chapter 6	Transport technology	Transported wastewater	System groups (table 5.4)
6.4.2.	Combined gravity sewer system	Stormwater + mixed black, brown, grey water Stormwater + grey water	4, 5 8, 9
6.4.3	Settled combined gravity sewer system	Stormwater + settled black, brown and grey water	
6.4.4	Gravity and pumped separate sewer system	Stormwater separate from mixed black, brown and grey water	6, 7, 10 – 12
6.4.5	Settled separate sewer system	Stormwater separate from settled mixed black, brown and grey water	
6.4.6	Vacuum transport	Black water	9, 11
6.4.7	Cartage transport	Urine, faecal matter, faecal sludge and digestate	8, 10, 12

A critical issue related to sewers is their maintenance and its concomitant costs. Sewer systems tend to accumulate solids, so that they need regular cleaning. If cleaning is inadequate, the transport capacity gradually diminishes with strong negative impacts on public health and the environment (Kolsky, 1998). After a discussion of the different transport technologies section 6.4 is completed with an overview of methane emissions, energy consumption (6.4.8 and 6.4.9), a screening matrix (table 6.4.5) and an assessment of strengths, weaknesses and conditions of most appropriate application of transport technologies (table 6.4.6). The costs of transport are reviewed in chapter 7.

6.4.2 Combined sewers (1 pipe) for stormwater and domestic wastewater

Plain combined sewers use one sewer network for transport of stormwater and all domestic wastewater streams. A typical feature of combined sewerage are strong differences between dry-weather and storm-weather flows. During dry weather the transported water is mostly wastewater discharged by households, public-commercial entities and industrial enterprises. In addition, infiltrate seeping into the system at high groundwater tables may increase the dry-weather flow. During rainfall combined systems convey large quantities of stormwater runoff. An example of dry-weather and wet weather flows and the required pipe diameters is given in box 6.1. The calculations show that flow and required pipe diameter of sanitary sewage are much smaller than the flow of sanitary sewage plus stormwater runoff under the assumed conditions.

Wastewater stream	Flow (m^3/s)	Required pipe diameter (m)
Sanitary sewage	0.017	0.25
Sanitary plus stormwater runoff	0.56	1.0

Assumptions: drainage area 10 ha, population 4,000 inhabitants: sewage quantity 120 l/cap.d; sewage peak factor 3; filling of sanitary sewer pipes at design flow 50%; velocity of flow 0.7 m/s; design rainfall intensity 60 l/ha.s; runoff coefficient 0.9; filling of pipes at wet weather design flow 100%; velocity of flow: 0.7 m/s.

Box 6.1 Comparison of required pipe diameters for dry and wet weather flow

Although separate sewerage has recently become the preferred technology, combined sewerage is probably the most widely used, as originally rapid discharge of all unwanted water was the main aim of sewers (Heip et al., 2001, p 100). Combined sewer systems are laid out underground, so that human exposure to the wastewater is prevented. In order to avoid frequent and costly de-sludging of sewer lines, the system should be designed to prevent the entrance of street litter as much as possible and to assure the self-cleansing of the pipes by providing sufficient slope. Another important measure to prevent clogging problems is the use of septic or interceptor tanks at household level (subsection 6.4.3). In situations with strong rains, the use of combined sewers requires pipes with large diameters that are usually less capable of retaining self-cleansing velocities at dry-weather flow. In areas with little natural slope self-cleansing is difficult to attain.

A typical disadvantage of combined sewers in combination with wastewater-treatment plants is the combined sewer overflows (CSO). They consist of a mixture of sewage and stormwater that is discharged untreated to the receiving surface water when the flow of stormwater exceeds the capacity of the transport sewers and/or the wastewater-treatment plant. Combined sewer overflows cause pollution of the receiving water which depends on the loads and frequency of the overflows. Frequency and volume of combined sewer overflows are usually reduced by 1) prevention of the runoff inflow, 2) increasing the storage capacity of the sewer system, and 3) providing storage capacity at the wastewater-treatment plant. In order to reduce runoff inflow and its pollution load several structural and non-structural measures are possible and recommended. Among the structural measures are the use of infiltration trenches and basins, and porous pavements. Non-structural measures include public awareness raising in order to prevent litter, street sweeping, fertilizer application control on grass areas and zoning restrictions to limit population densities (Tsihrintzis and Hamid, 1997). Storage capacity may be augmented by means of retention basins which reduce the volume of CSOs and their organic load through partial settling of suspended solids. After a rainfall event the wastewater stored in the basin is transported to the wastewater-treatment plant. Wiggers and co-authors (1977) show that the BOD_5 emission to surface water from a combined system via its CSOs is reduced from a range of about 100 – 250 g BOD_5/cap.yr at a storage of 3 mm to 20 – 50 g BOD_5/cap.yr at a storage of 10 mm, obtained with a retention basin. It can be concluded, that increase of the storage capacity by means of retention basins can lead to an important improvement to surface-water protection.

6.4.3 Settled combined sewers

Settled combined sewers are combined sewers in which the domestic wastewater is pre-treated on-site by means of a septic tank, Imhoff tank or another primary treatment technology. Pre-treatment may have important advantages as the effluent contains much less coarse and suspended solids, so that pipe diameters can be smaller and the risk of pipe clogging and the need of a high pipe gradient for generation of a sufficient self-cleansing velocity is reduced (small-bore sewerage: (Otis and Mara, 1985; Otis, 1986; Otis, 1996). This is particularly relevant where the supply of toilet flush water is not reliable and black water with high suspended solids content is discharged to the (combined) sewers. Accordingly, the settled sewer system could be less expensive to construct and maintain and be more reliable, especially in situations where the self-cleansing velocity is difficult to attain (see chapter 7, section 7.5).

Another strength associated with pre-treatment is the removal of part of the organic matter (in tropical areas up to 50% BOD_5 removal) at the expenses of the households, so that the on-site pre-treatment may be legally required where off-site treatment of sewage is lacking. This is the case in Vietnamese cities. The advantage of suspended solids removal at households is partially lost where high amounts of solids (sand, silt, plastics) enter the combined system through the rainwater inlets in the streets. This can be prevented by means of regular street cleaning and an appropriate design and regular maintenance of the rainwater inlets. The widespread use of household septic tanks also has disadvantages: methane emissions to the atmosphere, added construction and operational costs, and infiltration and exfiltration due to leakages of the septic tanks. Exfiltration may cause soil and groundwater pollution. Due to these disadvantages settled systems are assumed to have a lower performance with respect to methane emissions and soil/groundwater pollution than plain combined systems.

6.4.4 Separate sewer systems (2 pipes)

In separate sewer systems sanitary sewage and stormwater each have their own transport system. In the basic lay out of the separate system sanitary sewage is conveyed to a wastewater-treatment plant and runoff to surface water. The characteristics of both transport systems are described in the subsections below. The costs of separate systems increase with longer distances between the service area and surface water and thus greater length of the stormwater-transport system (ONRI werkgroep riolering, 2008, p 75). It should be noted that areas which have separate sewerage may nevertheless collect a part of the rainwater in the sanitary sewers (6.4.10).

6.4.4.1 Stormwater sewers and channels

The separate transport of stormwater occurs through pipes, open or covered channels or along the street surfaces and natural water courses. Channels or pipes are especially useful where annual rainfall and/or rainfall intensities are high, the runoff coefficient is high, the consequences of flooding are serious, and the transported runoff can be discharged or reused close to the place of origin. Street surfaces always have a function in stormwater drainage, but may be the dominant or only system if annual rainfall is low, incidental moderate flooding can be accepted and paved streets with sufficient slope are available.

Big stormwater runoff flows, as occur regularly in tropical cities, have to be evacuated to surface water as quickly as possible to avoid flooding in residential areas. Where fouling of stormwater transport systems with eroded soil and dumped solid waste is difficult to prevent, open channels are preferable, since they can be de-sludged much easier than closed pipes. As pointed out before, stormwater runoff can be considerably polluted with street dirt and sewage from wrong connections, so that its discharge may cause an unacceptable environmental damage. In order to reduce surface-water pollution, due to the discharge of untreated stormwater runoff, the separate sewer system can be adapted in a way that a large part of the polluted runoff and sewer sludge is led to the wastewater-treatment plant, and runoff is discharged only at high rainfall intensity (SSO = Storm Sewer Overflow). This system is called the *improved separate* or *integrated separate sewer system* (Heaney et al., 2000; Heip et al., 2001, p 109). Wiggers and co-authors (Wiggers et al., 1977) have calculated that a plain separate sewer system can have a much higher annual BOD_5 emission than a plain combined system due to its discharge of untreated surface runoff (SSO)[50]. The load of SSOs is greatly enhanced with an increase of wrong connections of house sewers to the stormwater sewers. By leading most of the rainwater runoff to the wastewater-treatment plant BOD_5 emissions from stormsewer overflows (SSO) can be drastically reduced. Alternatively, stormsewer overflows can be treated for example by means of constructed wetlands (Reed et al., 1995, p 261).

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[50] The BOD load emitted during stormwater overflows of a plain separate system was in the range of 200 – 550 g BOD/cap.yr (at 0% wrong connections). A plain combined system with a storage of 6 mm and 0.7 mm/h of pump overcapacity emits in the range of 60 – 140 g BOD/cap.yr. If for the separate and combined system *average* emissions of respectively 375 and 100 g BOD/cap.yr are assumed, the plain separate system emits 275 g BOD/cap.yr more than the plain combined system (Wiggers et al., 1977). If the annual load of a municipal sewer system is 54*365 = 19,710 g BOD/cap.yr and the BOD removal efficiency of the wastewater-treatment plant 95%, the annual discharge of the treatment plant to surface water amounts to 986 g BOD/cap.yr. Accordingly, stormwater overflows of a plain separate system can contribute substantially to the total BOD emissions of the system.

6.4.4.2 Plain sanitary sewers

Sanitary sewers are those sewers that transport domestic and public-commercial wastewater s*eparate from* stormwater. They are particularly advantageous where 1) the municipal wastewater is treated, and 2) the difference between the flows of sanitary sewage and stormwater runoff is big. These conditions are presently occurring in Vietnamese cities. The most basic separate system is option 6A (chapter 5), in which stormwater is discharged untreated and mixed black and grey water are transported to a wastewater-treatment plant. Where the gradients available for gravity flow in the sanitary system are limited, it may be advantageous to adopt septic tanks as pre-treatment technology: this is the settled sanitary sewer technology (6.4.5).

6.4.4.3 Simplified and condominial sewerage

In developing countries much effort is made to reduce the costs of sewer systems. This is done by diminishing the lengths of pipes and applying smaller diameters, less depth and more simple inspection pits. In condominial sewerage the pipes are laid out in yards and below sidewalks instead of in the streets, thus reducing the pipe length. Costs are also reduced by relying on community self-help. Literature about simplified and condominial sewerage usually refers to sanitary sewers and thus to separate sewer systems (Watson, 1995; Mara, 1996c; Melo, 2005). However, the attempt at cost reduction in developing countries extends to all sewer systems, especially to the relatively most expensive sections close to the households[51].

6.4.4.4 Pumped sanitary sewer systems

Pumping of domestic sewage can be necessary where full gravity transport is unfeasible. This is the case where sewage has to be transported through pressurized sewers from isolated settlements to a treatment plant over long distances, and where sewage has to be lifted locally to overcome a lack of gradient within a gravity system. Here, the emphasis is on the latter situation. The number of pumps per unit drainage area depends on the available gradient, maximum accepted depth of the sewer pipes, and the wastewater characteristics: wastewater pre-treated in septic tanks can be adequately transported at a lower gradient and therefore requires fewer pumping stations. For raw wastewater comminuting centrifugal pumps are recommended. Pumping increases the operation and maintenance requirements (costs) and the dependence on electricity supply and a well-organised institutional support of the system. The energy consumption and related costs of pumps depend on conditions of the terrain, flow-rate and pump efficiencies.

The system groups with separate sewerage (system groups 6, 7, 10 – 12) are subdivided into options without and with pumping of sewage. Pumped transport of combined sewage or separate stormwater is not included in the drainage and sanitation system options inventory in this thesis. Undoubtedly such systems may be required in low-lying areas where the collected runoff of a wide area has to be lifted to the main surface water system. (e.g. the pumping station of the Nhieu Loc Canal zone in Ho Chi Minh City and the Yen So pumping station near Hanoi).

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[51] Personal communication Mr Tran Van Thinh (Vietnam), 2007.

6.4.5 Settled sanitary sewers

On-site pre-treatment of wastewater before it is discharged to a sewer system is in particular useful where there is a high risk of clogging of pipes. This risk is largely diminished by removing the major part of solids from the domestic wastewater by means of septic or interceptor tanks (subsection 6.3.2). Separate sewer systems with on-site septic tanks are named settled separate systems (system options 6C-6F). On-site pre-treatment enables the application of sanitary sewer pipes with smaller diameters, the so-called small-bore sewers. The costs of a separate system can be significantly reduced, if small-bore sewers of considerable length are used instead of standard-bore sewers (chapter 7). Mara (1996a, p 17) points out that settled sewerage could be cheaper than simplified sewerage in communities where septic tanks are already in place.

6.4.6 Vacuum transport of sewage and black water

Vacuum transport can be applied in combination with regular flush toilet systems, but also with vacuum toilet systems. A vacuum transport system consists of a piped network of small diameter (90 – 250 mm) through which the wastewater is transported by means of the pressure difference between the atmosphere and a vacuum pump station. The vacuum pumps generate a pressure of 0.30 to 0.50 bar and the maximum possible distance between any inlet and the vacuum station is in practice about 6 km. The wastewater from a certain area is collected in a vacuum tank from where it is pumped to a wastewater-treatment plant. In flat terrain one station could serve an area of up to approximately 50 km^2 at a flow-rate of 200 - 300 l/sec[52]. A typical feature of a vacuum sewer system is the need of a vacuum valve at every point from where wastewater has to be evacuated. In the case of households with flush toilets the wastewater can be collected in a well by means of a small gravity-flow system from where it is transported by the vacuum system. Here, the vacuum valve is located in the collection well. Where vacuum toilets are used, each toilet is equipped with a vacuum valve. Vacuum systems are most known in applications where there is little water available for toilet flushing (e.g. airplanes, ships) and/or where gravity systems are difficult to construct or expensive. This is for example the case in areas with a very low building density. At decreasing density the relative costs per household of the gravity-sewer pipes increase strongly, while the costs of the vacuum-system per household increase much less, since they are not determined so much by the costs of the pipes, but by those of the vacuum-valve (Gruenert, 2002). In this chapter vacuum systems are proposed in combination with vacuum toilets for the concentrated collection and treatment of black water (options in groups 9 and 11). The main advantages of this system are very low flush water consumption, a somewhat reduced energy consumption, low emissions to the environment and an increased potential for the recovery of biogas, nitrogen and phosphorus (Zeeman et al., 2008). A detailed comparison between options is presented in chapter 7.

Since vacuum systems are technically more complicated than gravity systems, the system is deemed not appropriate in Vietnamese cities. In The Netherlands and Germany demonstration experiments with vacuum toilets and collection systems are being carried out near Luebeck (Germany) (Oldenburg et al., 2008) and Sneek (The Netherlands) (Meulman et al., 2008).

[52] Personal communication of Mr W.G.J. Gooren (Flovac Company, The Netherlands), 2007.

6.4.7 Cartage of sanitary liquids and solids

The drainage and sanitation options mentioned in this thesis produce several waste streams that have to be transported through cartage: sludge from septic tanks (septage), urine, dried faecal matter from urine-diverting dry toilets, and the digestate from black water digesters. In addition there is the waste collected during the cleaning of drainage and sewer systems. The collection of liquids can be carried out by means of vacuum devices including trucks, mechanized small vehicles with a vacuum tank (e.g. the Vacutug) and hand-driven vacuum pumps (e.g. the Mapet)[53]. For dry faecal matter transport in cities the use of suitable garbage trucks could be considered. Here, a few data on the energy consumption and costs of cartage are presented in order to enable comparison with other collection methods.

The energy consumption of cartage systems is mainly determined by the mass to be transported (kg/cap.yr), the fuel consumption of the transport vehicles (MJpe/tonne.km[54]) and the required transport distance (km). An estimate of the energy consumption in the carted collection of various waste streams is given in table 6.4.2.

The mass flows available for transport are calculated on the basis of generation rates of septage (0.11 tonne/cap.yr, Strauss et al, 1997)[55], urine (1.25 kg/cap.d with a recovery factor of 0.7 yields 0.32 tonne/cap.yr), dehydrated faecal matter + additives (0.1 tonne/cap.yr[56]), excreta in dry AAD toilets (1.7 kg/cap.d or 0.62 tonne/cap.yr) and excess sludge of UASB reactors treating concentrated black water (0.055 tonne/cap.yr)[57].
It has been assumed that the septage generation rates in septic tanks for sewage (black and grey water), mixtures of brown and grey water and black water alone are equal. The sludge accumulation rate in septic tanks for grey water alone is unknown but probably very limited. To the energy used for transport of faecal matter from dry urine-diverting dehydration toilets, the transport energy and costs of the supply of additives to the households have to be added. It has been assumed that additives are not freely available and have to be supplied to the users by means of motorized vehicles. To overcome the difficulty of different transport distances for the different waste streams, the fuel consumption is calculated per capita and per km of transport distance. Data about the fuel consumption of different types of trucks were found in Finnveden and co-workers (2000). That publication shows that fuel consumption depends on a score of factors, whose actual values in the systems described here are undetermined. As a consequence, for all types of transport the value of 4.4 MJpe/tonne.km was assumed, which corresponds to data used by Sonesson (1997) cited in Finnveden et al. (2000) for garbage collection trucks. The transport by means of light vehicles, like motorbikes, requires a much more energy per tonnekilometer. A refinement for the use of this type of light vehicles has been left out of consideration here.

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[53] http://www.akvo.org/wiki/index.php/MAPET_and_Vacutug_system.
[54] Energy consumption is expressed in MJ primary energy (MJpe).
[55] Ingallinella et al.,(1996) calculate a septage flow of 2 l/cap.d (= 0.73 m3/cap,yr) for an Argentinian town.
[56] It is assumed that faeces undergoes a weight reduction from 0.15 kg/cap.d to 0.07 kg/cap.d on dehydration. The assumed weight of additives is 0.2 kg/cap.d. The total dehydrated mass flow to be transported adds up to 0.27 kg/cap.d (99 kg/cap.yr).
[57] In lab-scale UASB septic tanks fed with concentrated black water Kujawa (2005, p 60) found an average total solids accumulation of 9.7 and 7.6 g TS/cap.d (at temperatures of 15 respectively 25^{o}C). If the accumulated sludge is thickened and transported at a TS concentration of 50 g/l, the annual slurry masses to be transported would be 71 and 55 l/cap.yr. Here, the latter figure is used.

Table 6.4.2 Energy consumption associated with cartage of excreta-related substances. Assumption: transport energy consumption: 4.4 MJpe/tonne.km (Sonesson, 1997).

Waste stream	Source	Mass flow (tonne/cap.yr)	Cartage energy consumption (fuel) (MJpe/(cap.km.yr))	Drainage and sanitation system group number
Septic tank sludge (septage)	Systems with septic tanks for sewage, brown water + grey water and black-water	0.11	0.48[58]	3 – 12
Urine (undiluted)	Systems with urine-diverting toilets	0.32	1.41	2, 5, 7, 8, 10, 12
Faecal matter plus additives	Systems with urine-diverting dry toilets	0.10	0.77[59]	2, 8, 10
Excreta	Systems with dry AAD toilets	0.62	2.73	1
Sludge	UASB reactors for treatment of concentrated black water	0.055	0.24	9, 11

It can be concluded from table 6.4.2 that the energy input of cartage is highest (2.73 MJpe/cap.km.yr) where dry toilets are used and wet, partly digested, excreta (mixed urine and faeces) is transported. Also a relatively high energy input may be needed for urine-diverting dry toilets with cartage of urine (1.41 MJpe/cap.km.yr) and faecal matter (0.77 MJpe/cap.km.yr). These potential high energy demands make clear that the transport distances should be kept as small as possible. Using recent data of septic-tank sludge transport in Ho Chi Minh City it can be estimated that about 15% of the transportation revenues are spent on fuel.

6.4.8 COD conversion and methane emissions in sewers

Methane emissions from sewers are associated with retention times longer than approximately 4 hours under anaerobic conditions (Guisasola et al., 2008). Such conditions occur for example in rising mains of pumped sewer systems. The methane escapes as soon as the sewage is exposed to ambient air in ventilated parts of the sewer system or in the wastewater-treatment plant. In rising mains at temperatures between 25^o and 30^o C Guisasola and co-workers (2008) found dissolved methane concentrations between 20 and 120 mg CH_4-COD/l[60]. Lab-scale simulation of methane formation from sewage in pipes with an anaerobic biofilm showed a rapid increase of the methane concentration to about saturation concentration in 7 hours (T = 21 ^{o}C). On the basis of these preliminary data it is assumed here

[58] Cartage energy is equal to mass flow times energy consumption. In this case: 0.11*4.4 = 0.48 MJpe/cap.km.yr.

[59] The energy required per tonne.km is higher than 4.4 MJpe/tonne.km, since also the energy for transport to the households of ash for coverage of faecal matter has been included.

[60] The methane saturation concentration at a partial pressure of 1.0 atm. and a temperature of 25^o C is 22 mg CH_4/l which represents 88 mg CH_4-COD/l.

that in systems with pumped sanitary sewers with rising mains the methane generation rate and loss to the atmosphere equals 10% of the influent COD load which corresponds to approximately 11 g CH_4-COD/cap.d (2.7 g CH_4/cap.d) for unsettled sewage. In ventilated gravity systems and at short retention times the methane production is probably much lower. Accordingly, the methane emission from conversions in pipes of these systems has been neglected. Methane emissions from on-site storage and treatment technologies are described in section 6.3, table 6.3.3. The lowest CH_4 emissions are expected from gravity systems without septic tanks; the highest emissions from pumped systems with septic tanks.

6.4.9 The energy consumption of transport technologies

In the drainage and sanitation systems presented here energy is consumed due to various forms of transport: pumping of sewage, vacuum transport of black water and cartage of urine, and wastewater-related slurries. Table 6.4.3 gives an overview of the energy consumption of drainage systems. The energy consumed expressed as primary energy (MJpe/cap.yr) is found by taking into account an efficiency of the conversion of primary energy to electricity of 33%.
The per capita consumption of energy of a system depends strongly on local conditions. In pumping and vacuum transport the required electrical energy is in the first place determined by the morphology of the terrain. Other important factors are the quantities of wastewater transported, population density, the size of the catchment area and the efficiency of the used equipment. Energy consumption is small to negligible in gravity systems without lifting stations, but if natural gradients are insufficient external energy is needed for transport.
If pumping or vacuum transport is needed, the energy costs per capita increase with decreasing population density due to an increasing average pipe length per inhabitant. Increasing size of the service area has a slightly reducing effect on the energy consumption per capita as increasing size implies a relative large fraction of pipes with a large diameter and hence lower head loss per unit of length.
According to the Dutch Sewerage Guidelines (RIONED, 2002) the costs of electrical energy spent on sewage transport in The Netherlands are 2.5 Euro/hh.yr. At an electricity price of 0.08 Euro/kWh the energy consumption is 31 kWh/household.yr or 43 MJe/cap.yr (2.6 persons/ household). In a comparison of gravity sewerage and vacuum transport (using regular flush toilets) Gruenert (2002) mentions an electricity consumption of 71 MJe/cap.yr for gravity-flow sewerage combined with lifting stations (213 MJpe/cap.yr), and 52 MJe/cap.yr (157 MJpe/cap.yr) for a vacuum-sewer system. For vacuum systems carrying concentrated black water plus kitchen garbage from vacuum toilets and kitchen waste grinders the electricity consumption would be 108 MJpe/cap.yr (Zeeman et al., 2008). Table 6.4.3 summarizes the energy consumption data of sewers and cartage systems. The mass flow data for cartage have been taken from table 6.4.2.

Table 6.4.3 Primary energy consumption for the transport of various waste streams Assumption: in cartage the transport distance (one direction) is 5 km.

Transport mode	Material	Mass transported (tonne/cap.yr)	Energy use for cartage (MJpe/t.km)	Transport distance (km)	Energy consumption (MJpe/cap.yr)
Gravity sewers with lifting stations	Sewage	44	0	n.a.	213[61]
Gravity sewer without lifting stations	Sewage	44	0	n.a.	15[62]
Vacuum sewers	Sewage	36	0	2.5	157[63]
Vacuum sewers + kitchen waste grinders	Concentrated black water from vacuum toilets	2.2	0	n.a.	108[64]
Cartage	Urine	0.32	4.4	10	14.1[65]
Cartage	Faecal matter from dehydrating UD toilets	0.10	4.4	10	4.4
Cartage	Excreta from AAD toilets	0.62	4.4	10	27.3
Cartage	Sludge from from UASB-septic tanks	0.055	4.4	10	2.4

It can be concluded from the data of table 6.4.3 that there is a large difference between the energy consumption of gravity systems with and without lifting stations and that the difference between the various mechanized piped transport systems is relatively small. The energy consumption from sewer systems with lifting stations (71 MJe/cap.yr (= 213 MJpe/cap.yr)) and an average of 2.6 persons per household) results in an electricity consumption of 185 MJe/hh.yr equal to a continuous power of 6 W/hh. In The Netherlands direct energy costs are an extremely small fraction (about 1.5%) of the total costs of sewerage (172 Euro/hh.yr) (RIONED, 2002). The transport by means of cartage consumes less energy than by means of sewers by virtue of the much lower mass flow of the former. According to table 6.4.3 the transport of urine and faecal matter associated with dehydrating urine-diverting on-site toilet systems would take approximately 18 MJpe/cap.yr, which in the same order as gravity sewers without lifting stations.

61 (Gruenert, 2002). Sewage generation rate: 120 l/cap.d.

62 Assumed is one bottom-end pumping station to lift water into a wastewater-treatment station (total head: 12m).

63 (Gruenert, 2002).

64 (Zeeman et al., 2008).

65 Energy consumption (MJpe/cap.yr) = mass transported (tonne/cap.yr) * energy use (MJpe/ tonnekilometer) * distance (km).

6.4.10 Selection of transport systems

In areas with a high building density transport of excreta and domestic wastewater out of the area is usually required. For the choice of off-site instead of on-site treatment of wastewater Mara (1996a, p 14) mentions a critical in-house water consumption of 100 l/cap.d and a population density of 200 capita/ha. The first parameter points at the limited capacity of septic-tank effluent percolation into the subsoil, the second at the building density at which simplified sewerage would be cheaper than on-site treatment (Sinnatamby (1983), cited in Mara (1996a, p 15).

In this subsection a screening aid for the selection of transport systems is elaborated summarized in the tables 6.4.4, 6.4.5 and 6.4.6. The system options regarding transport technologies are gravity and pumped combined sewerage, gravity and pumped separate sewerage, vacuum transport and cartage of excreta. As vacuum transport and cartage have very specific conditions of most appropriate application[66], the main selection problem is between combined and separate systems. As explained above combined systems have long been the dominant sewer system in cities everywhere in the world. The disadvantages of this system as compared to the separate system have become apparent in particular when wastewater treatment became a standard practice, and high requirements were put to the environmental protection of surface water. These disadvantages are associated with the enormous peak flows of stormwater; the most important are (1) pollution of surface water with combined sewer overflows, (2) a high hydraulic capacity of pumping stations and treatment works and fluctuating sewage strengths, (3) deep sewer layout, (4) diluted sewage in the street at flooding events, (5) disturbance of the natural surface water regime in the sewered area. Advantages of the system as compared to separate systems are lower costs, simpler and cheaper house connections, a certain degree of stormwater treatment and better self-cleansing conditions (Berlamont, 1997, p 14; Butler and Davies, 2000, p 23). As indicated above some of the disadvantages are mitigated in the improved combined system by means of increased storage capacity.

[66] The conditions of most appropriate application of vacuum sewerage occur in situations with very low quantities of flushing water (air planes, ships, eco-buildings) and/or complicated and expensive construction of gravity and pressure pumped systems (rocky soil, dispersed buildings). The conditions of most appropriate application of cartage are associated with the use of dry toilets (subsections 6.4.6 and 6.4.7).

Table 6.4.4 Infrastructure-related physical, environmental, social, cultural, economic and financial factors that determine transport system choice.

Nr	Influencing factor	Consequences to sewer system choice
	Infrastructure and physical factors	
1	Absence of piped water supply	If there is no piped water supply in the community, sewerage is not applicable. **Cartage** of excreta is the preferred system option. Stormwater may be transported by **gravity channels**.
2	Rainfall regime	Rainfall regime has impact on the choice of the stormwater system; a) very high intensities lead to high peak flows: **separate sewers** with direct discharge to surface water; also use of street surfaces b) low and moderate intensities: possibility of both **separate and combined sewers**; use of street surface for stormwater transport is possible c) very low intensities/low monthly rainfall: **sanitary sewers only**; rainwater discharges via street surface.
3	Distance to surface water	The longer the distance between the serviced area and the nearest point of discharge of stormwater the higher the extra costs of separate systems. At long distances therefore **combined sewerage** would be preferred.
4	Natural slope of terrain	At insufficient slope for gravity flow there is a need to apply **pumping of sewage. On-site solids removal prior to discharge** into the sewer system may reduce the risk of pipe clogging. At sufficient slope: possibility to use surface (streets) for drainage of stormwater, reduced need of pumping.
5	Low flow of domestic wastewater	If water supply is intermittent and/or pour-flush toilets are used, wastewater generation is due to be low. To prevent sewer clogging household **on-site pre-treatment of sewage with septic tanks** is preferred. If cistern-flush or dual flush toilets are used the black water can be discharged to **combined or sanitary separate sewers without pre-treatment**.
6	Character of the soil	If the soil is rocky, the lay out of gravity sewers is difficult. **Pressurized or vacuum sewerage** are preferable for sanitary sewage.
7	Type of built-up area	In areas with strong pollution of the streets (e.g. markets) stormwater has to be transported to the WWTP. Preference for **combined sewerage or improved separate sewerage.**
8	Availability of on-site pre-treatment	If domestic sewage is treated on-site by means of a septic tank, **small-bore sanitary sewers** can be applied.
9	Nature of street pavement	If street pavement is of bad quality, erosion and the risk of clogging of closed pipes may be high. In this case **open channels or transport via natural watercourses** are preferred for stormwater runoff transport.

Table 6.4.4 (continued) Infrastructure-related physical, environmental, social, cultural, economic and financial factors that determine transport system choice.

Nr	Influencing factor	Consequences to sewer system choice
10	Deficient solid-waste management	If there is a high risk of street litter entering sewer systems, transport of *stormwater* by closed pipes should be discouraged. In this case **open channels and transport via street surfaces** are preferred for stormwater discharge, and **separate closed pipes** for sanitary sewage
	Environmental factors	
11	Environmental regulations	If high requirements are put to prevention of emissions via CSOs and SSOs, **improved combined** or **improved separate systems** are preferred.
12	Water reclamation and reuse	If there is a strong need to reclaim and reuse water, soil infiltration of stormwater and advanced treatment of sanitary sewage is recommendable. In this case a **separated sewer system** is preferred.
	Social and cultural factors	
13	User acceptance	Users may prefer a certain transport system even if other options could be better, or conversely may reject a certain system. This may be a reason to apply/not apply that system in order to warrant a sense of ownership of the system.
14	Institutional acceptance	Involved local institutions may prefer a certain transport system even if other options could be better or conversely reject a certain system. This may be a reason to apply/not apply that system in order to warrant a sense of ownership of the system.
15	Reliability of correct construction	If a large percentage of wrong connections of sewage to the stormwater drainage system is expected, combined sewerage is a better option for environmental reasons.
16	Reliability of maintenance	If regular maintenance to prevent clogging is not warranted, open pipes for stormwater transport are recommendable.
	Economic/financial factors	
17	Available money for construction per household	If public financial means are very scarce, capital investment on wastewater transport should be minimized in order to make a system affordable. Stormwater transport makes use of natural waterways and streets. In critical areas open channels and drains may be used. Domestic sewage may be collected by simplified/condominial sewerage.
18	Available money for O&M per household	If the public means for operation and maintenance are very limited the recommendable choice for the sanitary sewers may be a system with on-site solid removal in septic tanks. Stormwater runoff may be discharged via streets or open channels. Such a **settled separated system** has probably the lowest public O&M costs. Part of the O&M- cost burden is transferred to the households who have to de-sludge their septic/interceptor tanks.

Given the significant disadvantages of combined systems, nowadays the separate system is preferred under most conditions (Berlamont, 1997, p 17). Where a combined system already exists its reconstruction to a separate system depends much on local conditions and requirements (ONRI werkgroep riolering, 2008). An example of such a reconstruction in Vietnam is found in Buon Ma Thuot City (Corning, 2006).

Often existing combined systems are connected to the sanitary sewers of a newly developed separate system. This leads to a *hybrid* or *partly separate sewer system* (Butler and Davies, 2000, p 25). In areas of new sewer development hybrid systems may also be appropriate where there is a lack of space for a double pipe system, the lay out of separate rainwater collection pipes is not cost-effective, or a high risk of pollution of the stormwater runoff exists (parking lots, busy streets). In such cases, local combined systems are provided.
In the table 6.4.4 above an overview is given of the factors that influence the choice between the various transport systems. Some of these factors can be considered as *restrictive*, so that they distinguish between feasibility or unfeasibility of transport options in the screening matrix (table 6.4.5). These restrictive factors are the influencing factors 1 until 6 mentioned in table 6.4.4. The remaining factors (7-19) influence system choice as well, but they are not considered restrictive and are not explained in detail further. The restrictive factors that determine the choice of transport systems are of importance as well for the *overall* drainage and sanitation system choice (figure 6.7.1 and 6.7.2). Therefore the implications of these factors (1-6) are discussed in detail here.

Absence of piped water supply (factor 1) renders transport through sewers unfeasible. Under this circumstance on-site dry sanitation systems are required.
As *rainfall regime* (*annual precipitation and intensity*) (factor 2) has a big impact on the dimensions and functioning of sewer systems, the meaning of climatic conditions to sewer system choice is discussed here. In tropical climates with a high annual rainfall of more than 1000 mm and incidental high rain intensities combined transport would lead to the need of numerous overflow devices to avoid the transport of excessive flows and extremely large pipe diameters (e.g. > 2.5 m diameter). Due to the large-diameter pipes, it would be difficult to maintain self-cleansing velocities at dry-weather flow in such a combined system. The solids accumulated in the pipes during the dry season would probably be, at least partly, washed away in the rainy season, providing some cleansing of the pipes, but causing significant surface-water pollution via the combined sewer overflows. Moreover, stormwater flows seem rarely able to provide efficient cleaning, so that the combined pipes would require considerable maintenance (Kolsky, 1998, p 12). It may be concluded therefore that in cities in the humid tropics *separate systems* are highly preferable (Berlamont, 1997, p 14).
In moderate climates with rainfall intensities that are much less extreme than in the humid tropics combined transport is much more feasible than in the tropics. The frequency of high rainfall intensities is lower than in the humid tropics, so that a much larger part of the stormwater runoff can be transported to the wastewater-treatment plant and less has to be discharged without treatment. Nevertheless, also in moderate climates separate sewer systems are preferred nowadays for the reasons explained above.
In dry climates with average annual rainfall between 200 and 500 mm, the monthly rainfall often does not exceed 100 mm. During a large part of the year rainfall is scarce. An example of a city with such a dry climate is. Amman (Jordan) (annual/max. monthly rainfall: 273/63

mm)[67]. Under such conditions incidental flooding may cause hindrance, but recovery of all fresh water for reuse, especially rainwater, is of high importance. Therefore a transport system should be chosen that helps to prevent flooding in sensitive areas and also maximizes infiltration and recovery of rainwater. Combined sewers are feasible as part of the system, but separate sewers especially with stormwater handling along street surfaces and open channels seem preferable.

In cities with an annual rainfall less than about 200 mm (e.g. Cairo: 25 mm, and Lima: 20 mm) a high rainfall intensity is extremely rare. In such situations it is not worthwhile to allow entrance of the scarce rainwater (with street dirt) to the sanitary sewer system. Stormwater runoff, if any, can be transported and infiltrated via street surfaces and channels and is kept separated from sewage.

The *transport distance* (factor 3) from the sewered community to the point of stormwater disposal has an impact on the technology choice in that a *short distance and a condition of sufficient slope for gravity flow* renders separate systems relatively inexpensive as the length and depth of stormsewers is modest. If however under the same conditions of sufficient slope the *distance is long*, the preference for separate systems is less outspoken as the costs of separate systems exceed those of combined systems. In this case both combined and separate systems may be selected. The *availability of sufficient slope for gravity flow* (factor 4) excludes systems options with pumping of wastewater.

A system for transport of stormwater and sewage to a wastewater-treatment plant has to be selected for a densely built, low-lying area with an extremely low slope of the terrain. The soil consists of a sand/clay mixture. There is intermittent water supply and a high annual rainfall volume and intensity. The transport distance of the sewage to the wastewater-treatment plant is long. Stormwater runoff can be discharged to surface water in the vicinity of the drainage area.

From table 6.4.5 can be inferred that the systems implementable under the restrictions of high rainfall (consequence: separate sewer system), short distance to disposal of stormwater and sufficient slope for gravity flow (consequence: gravity stormwater channels); lack of slope for gravity flow of sewage and long distance to the wastewater-treatment plant (consequence: need of sewage pumping), and intermittent water supply (consequence: on-site solids removal) are:

- gravity stormsewers
- pumped settled sanitary sewers.

Jointly they form the separate settled system with pumping of sewage. In chapter 5 this is option 6C (P) (all sewage through septic tank) or option 6E (P) (only black water through septic tank). Gravity settled sanitary sewers can be applied where the distance to the wastewater-treatment plant is not too long. Nevertheless, pumping of sewage to the level of the entrance of the wastewater-treatment plant is usually required. It has been assumed that despite the low terrain gradient gravity stormwater runoff can be applied.

Box 6.2 Example of transport technology selection

[67] Rainfall data from http://www.worldclimate.com (accessed on January 29, 2010).

Factors that lead to a reduction of self-cleansing capacity, such as *intermittent water supply* (factor 5) and a *lack of slope* of the terrain may lead to sewer blockages. Under these circumstances plain combined and plain separate systems are less suitable and settled systems with on-site solids removal and pumped system options are preferable. If there is a *lack of slope for gravity flow* the selected system options could be a pumped combined system or a separate system with channels for stormwater transport and pumping of sanitary sewage.
Where the *soil is rocky* (factor 6) the costs of sewer construction may be very high. Under this condition transport by vacuum lines or cartage may be preferable.

6.4.11 Strengths, weaknesses and appropriate application of transport technologies

In order to facilitate the selection of the most appropriate sewered transport technology table 6.4.6 summarizes the strengths, weaknesses and conditions of most appropriate application which were pointed out in this section. It can be concluded from this table that separate sewer systems can be applied under a wider range of climatic conditions than combined systems and that (high) requirements to the protection of surface water, and thus reduction of loads of CSOs and SSOs, lead to the choice of improved combined and integrated separate systems.

Table 6.4.5 Screening matrix for urban wastewater-transport technologies.
(+ = feasible/ preferable; - = unfeasible/ less preferable; X = factor irrelevant to technology choice)

Transport technologies	Gravity combined sewer	Gravity settled combined sewer	Pumped combined sewer	Gravity stormwater channels or pipes	Gravity sanitary sewers	Gravity settled sanitary sewers	Pumped sanitary sewers	Pumped settled sanitary sewers	Vacuum transport black water	Cartage of excreta
Options (chapter 5) / Restrictive factors	4A, B 5A, B	4C-F 5C-F	Options not included	All options of groups 6-12	A, B options of groups 6-12	6C-F 7C-F	A, B options of groups 6-12 (P)	6C-F (P) 7C-F (P)	9A, B 11A, B	1A, B
Absence of piped water supply	-	-	-	X	-	-	-	-	-	+
High annual precipitation and intensity	-	-	-	+	+	+	+	+	X	X
Medium and low annual precipitation and intensity	+	+	+	+	+	+	+	+	X	X
Very low annual precipitation	-	-	-	-	+	+	+	+	X	X
Long distance to disposal of stormwater; sufficient slope for gravity flow	+	+	-	+	+	+	-	-	X	X
Short distance to disposal of stormwater; sufficient slope for gravity flow	-	-	-	+	+	+	-	-	X	X
Lack of slope for gravity flow of sewage[68]	-	-	+	+	-	-	+	+	+	+
Intermittent piped water supply	-	+	-	X	-	+	+	+	-	+
Rocky soil	-	-	-	-	-	-	-	-	+	+

[68] Where the terrain lacks the slope for gravity flow the choice is between a pumped combined system or a pumped separate system with stormwater channels that accommodate gravity flow despite the lack of slope of the terrain. Pumping of stormwater runoff could also be necessary, but this option is not included here.

Table 6.4.6 Strengths, weaknesses and conditions of most appropriate application of sewered transport technologies.
(CSO = combined sewer overflow; SSO = storm sewer overflow. Medium rainfall height ranges from 500 – 1000 mm/yr (indicative)

Sewer technologies	Plain combined	Improved combined	Settled combined	Improved settled combined	Plain separate	Improved separate	Settled separate	Improved settled separate
Options (chapter 5)	4A 5A	4B 5B	4C, E 5C, E	4D, F 5D, F	6A 7A	6B 7B	6C, E 7C, E	6D, F 7D, F
Strengths	Most simple combined system with lowest costs	Reduced surface water pollution caused by CSO loads	Reduced risk of clogging	Reduced surface water pollution caused by CSO loads; reduced risk of clogging	Most simple separate system	Reduced surface water pollution caused by SSO loads	Reduced risk of clogging of sanitary sewers	Reduced surface water pollution caused by SSO loads; reduced risk of clogging of sanitary sewers
Weaknesses	Surface water pollution due to CSO loads; risk of clogging; unsuitable at high rainfall intensities	Risk of clogging; unsuitable at high rainfall intensities	Surface water pollution due to CSO loads; unsuitable at high rainfall intensities; need of septic tanks	Increased costs; unsuitable at high rainfall intensities; need of septic tanks	Surface water pollution caused by SSO loads; risk of clogging	Risk of clogging of sanitary sewer	Surface water pollution caused by SSO loads; need of septic tanks	Increased costs need of septic tanks;
Conditions of most appropriate application	Medium annual rainfall and intensity; no high requirements to reduction of CSO loads	Medium annual rainfall and intensity; high requirements to reduction of CSO loads	Medium annual rainfall and intensity; no high requirements to reduction of CSO loads; low and irregular flush water volumes; low slope of terrain	Medium annual rainfall and intensity; high requirements to reduction of CSO loads; low and irregular flush water volumes; low slope of terrain	Any annual rainfall volume and intensity; short distance to disposal of stormwater; no high requirements to reduction of SSO loads	Any annual rainfall volume and intensity; short distance to disposal of stormwater; high requirements to reduction of SSO loads	Any annual rainfall volume and intensity; short distance to disposal of stormwater; no high requirements to SSO loads; low and irregular flush water volumes; low slope of terrain	Any annual rainfall volume and intensity; short distance to disposal of stormwater; high require-ments to reduction of SSO loads; low and irregular flush water volumes; low slope of terrain

6.5 Off-site treatment of municipal wastewater

The aim of this section 6.5. is to support the selection of appropriate treatment technologies for municipal sewage. The section presents the characteristics of off-site treatment technologies for different types of wastewater and screening aids for the selection of feasible technologies.

6.5.1 Overview of waste streams

In chapter 5 twelve different system groups of drainage and sanitation chains were distinguished, each of them producing their characteristic kinds of wastewater (table 5.3). System group 4 until 12 comprise the off-site sanitation systems. Table 6.5.1 presents the wastewater streams associated with these system groups and the subsection of this chapter where the treatment of these streams is discussed.

Table 6.5.1 Overview of waste streams and reference to subsections and system group classification.

Waste (-water) stream	Subsection	Sanitation system group
Mixed black, grey and stormwater	6.5.2 – 6.5.5	4
Mixed brown, grey and stormwater		5
Mixed black and grey water		6
Mixed brown and grey water		7
Concentrated black water and kitchen waste	6.5.6	9, 11
Grey water and stormwater	6.5.7	8, 9, 10, 11, 12
Grey water		8, 9, 10, 11, 12
Urine	6.5.8	2,5,7,8,10
Faeces	6.5.9	1, 2
Faecal sludge (septage)		All
Treatment sludge		All

Sections 6.5.2 - 6.5.4 discuss off-site treatment technologies of all types of sewage, i.e. mixed black water, brown water, grey water and stormwater. The outcomes of these subsections are summarized in a screening aid in subsection 6.5.5. Subsections 6.5.6 and 6.5.7 discuss respectively the treatment of source-separated concentrated black and grey water. Urine treatment is reviewed in section 6.5.8 and the treatment faecal sludges and sludges from wastewater-treatment plants in 6.5.9. An overview of the energy consumption of wastewater-treatment options is presented in subsections 6.5.10. A screening tool for technologies used for source-segregated wastewater streams is finally introduced in subsection 6.5.11. The methodology of the estimation of land use of the wastewater-treatment technologies reviewed in this chapter is given in appendix 6.1.

6.5.2 Classification of off-site treatment technologies for sewage

Off-site treatment systems, as conceived in this chapter, consist of a series of preliminary, primary and secondary treatment stages having as main functions removal of coarse wastes and sand, settleable solids and reduction of the oxygen demand. In systems with on-site pre-treatment of black, brown and grey water and separate transport and discharge of stormwater the off-site the primary treatment step might be omitted, depending on the characteristics of the sewage in terms of COD, BOD_5 and TSS. Where stormwater is received at a treatment station, it is assumed that full preliminary, primary and secondary treatment are required. The technologies are further differentiated into non-mechanized and mechanized, an important distinction, since in developing countries non-mechanized treatment methods are deemed more reliable than mechanized technologies (Sasse, 1998). A third distinction is the capacity of the treatment plant (m^3/d). Mechanized technologies with short hydraulic retention times can in general be used at any scale, but non-mechanized technologies with long retention times are limited to plants of smaller capacities. It is however impossible to indicate the maximum applicable capacity of a technology independent of the situation under study[69].

An overview of the wastewater-treatment technologies discussed in this chapter is presented in table 6.5.2. The subdivision into the categories *preliminary, primary and secondary* treatment indicates the proposed order in the treatment plant lay-out rather than the type and efficiency of treatment achieved. The UASB-reactor as an example, which is designated here as a primary treatment technology, achieves both removal of solids and dissolved organic matter with an approximate BOD_5 removal of 80% and could therefore compete with aerobic secondary treatment technologies like the trickling filter. The table does not intend to suggest that all primary technologies can be suitably combined with *all* secondary/post-treatment technologies. In the last column the capacity ranges in which the several technologies can be feasibly used are tentatively indicated. Restrictions to the capacity on the low side can be put by relatively high costs of small mechanized aerobic plants. Restriction on the high side are put by the costs of carrier material (aerated fixed film reactors, constructed wetlands), the required land (ponds and constructed wetlands), or construction costs (Imhoff and Dortmund tank, anaerobic upflow filter). Reactor types without carrier material or with very cheap carrier material and relatively short retention times (high-rate activated sludge plants, trickling filters) have no limit to the maximum capacity.

With the mentioned technologies a considerable number of technology chains can be composed, such as for example:

1. Coarse screen + grit removal + anaerobic ponds + facultative + maturation ponds;
2. Coarse screen + grit removal + sedimentation + activated sludge process;
3. Coarse screen + grit removal + UASB reactor + downflow hanging sponges (DHS) tower.

The many imaginable primary and secondary wastewater-treatment chains vary with respect to their treatment efficiencies. The technologies described here are basically aiming at the removal of suspended solids and organic matter. They remove nitrogen and phosphorus compounds only to a small degree, though effluents with low nitrogen and phosphorus concentrations may be reached, if at-source urine separation is applied. This form of at-source separation reduces the nitrogen and phosphorus loads in wastewater. In absolute terms the effluent quality attained will depend much on the quality of the influent, which in its turn is determined by local circumstances.

[69] Several cities in warm countries have stabilization pond systems with a large capacity and footprint, e.g. the city of Amman (Jordan) was served until recently by the stabilization ponds of the Khirbet As Samra plant with a design capacity of 68,000 m^3/d (Duqqah, 2002, p 53; Halalsheh, 2002, p 28).

Table 6.5.2 Off-site wastewater-treatment technologies presented in this chapter and their indicative capacity ranges.

Type	Preliminary Treatment	Primary Treatment	Secondary/ post-treatment	Indicative capacity range (m^3/d)
Non-mechanized[70]	Bar screen Grit removal	Anaerobic pond Facultative pond UASB-reactor	Facultative pond Maturation pond Rapid soil infiltration	100 - 10,000
		Imhoff tank Dortmund tank VF Constr. Wetland	Anaerobic Upflow Filtration Subsurface Flow Constr. Wetland	10 - 500
Mechanized	Mechanical screen Sieve Grit removal	Sedimentation tanks Chemically enhanced sedimentation tanks	Activated sludge Trickling Filter	Any capacity higher than 100
			Oxidation ditch Mobile Bed Bioreactor Rotating Biological Contactor Submerged Aerated Fixed-Film Reactor Downflow Hanging Sponges Tower	100 - 10,000

6.5.3 Non-mechanized treatment technologies for sewage

This subsection discusses characteristics and strengths and weaknesses of non-mechanized treatment technologies applicable at small-scale and larger scale. The collected data are summarized in the tables 6.5.3 (small-scale) and 6.5.4 (larger scale).

6.5.3.1 Preliminary treatment

The preliminary treatment at an off-site non-mechanized wastewater-treatment plant usually consists of removal of coarse materials by means of bar screens and removal of sand by means of a grit removal device (sand trap). Where through the use of separate sewer systems the influent carries little sand, the grit removal device is not necessary.

6.5.3.2 Primary treatment with anaerobic and facultative ponds

The treatment processes in *anaerobic ponds* are sedimentation and anaerobic digestion. Primary treatment of municipal wastewater with anaerobic ponds is usually followed by further treatment by means of facultative and maturation ponds. The hydraulic retention time of anaerobic ponds for municipal wastewater usually ranges from 1 to 2 days. The volumetric organic loading rate may vary between 0.1 and 0.4 kg BOD/m^3.d, and the depth is from 3 to 4 meter (Arthur, 1983, p 18). Land requirement is about 0.1 m^2/capita. The BOD_5-removal efficiency at 20 – 25 ^oC and an HRT of 1 – 2 days is in the range of 40 – 60% (Reed et al., 1995, p 119). Strengths of anaerobic ponds are their great simplicity of construction and

[70] Non-mechanized technologies may include electrical pumps for lifting the influent or effluent.

operation, high flexibility and reliability, and reasonable sludge stabilization. Weaknesses are the relatively high land requirement, unhindered escape of methane gas to the atmosphere, and the possibility of malodors and insect nuisance. The technology is not recommendable inside built-up areas. *Facultative ponds* are mostly applied for secondary treatment after anaerobic ponds or UASB reactors, but can also be used as a primary treatment method when the organic matter concentration in the influent is low. Due to the low admissible organic loading rates, the per capita surface area of facultative ponds as a primary treatment method is relatively large, and consequently they are limited to small scale applications. Their strength is a very low maintenance requirement.

6.5.3.3 Primary treatment with UASB reactors

Similar to anaerobic ponds UASB reactors remove organic matter by means of sedimentation and anaerobic digestion. Crucial differences with the anaerobic-pond technology are a more intensive contact between influent and sludge, brought about by the induced upflow mode and the even distribution of the influent over the reactor's bottom, and the presence of a gas-solids-liquid separator at the top of the reactor. The functions of the gas-solids-liquid separator are the retention of sludge and the capture of biogas for subsequent utilization. At an ambient temperature of about 25^{o} C the hydraulic retention time in UASB reactors for sewage usually ranges between 6 and 10 hrs. The reactor depth is in the range of 4 to 6 m. The maximum upflow velocity is about 1.0 m/hr (Van Haandel and G. Lettinga, 1994, p 65). Land requirement of an UASB reactor with sludge drying beds is about 0.05 – 0.1 m^2/cap. The BOD_5 removal efficiency is in the range of 65 – 85%; the COD removal 60 – 75%. The performance drops with decreasing temperature. The sludge production rate in the treatment of domestic wastewater is 0.1-0.2 kg TSS/kg COD applied (Von Sperling and De Lemos Chernicharo, 2005, p 763). The amount of generated biogas (COD_{gas}) based on raw domestic sewage under tropical conditions is 50 – 60% of the influent COD load (Leitao, 2004, p 19). Taking into account the fraction of methane that leaves the reactor dissolved in the effluent[71], the captured methane amounts to about 10 g CH_4/cap.d, which corresponds to 184 MJpe/cap.yr[72]. Stable operation in full-scale UASB reactors under tropical conditions was obtained at influent COD_{tot} concentrations varying between about 200 and 750 mg/l. The COD_{tot} concentration in the effluent of tropical UASB reactors fed with raw sewage operated at HRT values between 6 and 12 hours lies in the range of 90 – 150 mg/l (Van Haandel and Lettinga, 1994, p 102; Florencio et al., 2001). As the COD removal efficiency of the process decreases with decreasing strength of the influent, these reactors are deemed less appropriate for very diluted wastewater (COD_{inf} < 200 mg/l (Leitao, 2004, p 32).

Strengths of UASB reactors are the possibility of energy production, the high BOD_5 reduction in comparison with other anaerobic primary treatment technologies, which enables the use of relatively simple post-treatment technologies, the small footprint and the low production of well stabilized excess sludge. The effluent of UASB reactors often does not satisfy discharge or reuse requirements, but aerobic post-treatment is relatively easy and may produce a well stabilized sludge if the produced aerobic sludge is recirculated to the UASB reactor

[71] The solubility of methane in water at 25 ^{o}C and atmospheric pressure is 21.6 g/m^3. At a partial pressure of methane in biogas of 0.75 atm the solubility is 16.2 g CH_4/m^3 (64.8 g CH_4-COD/m^3). In the treatment of raw sewage (COD_{inf} load = 109 g/cap.d; Q = 0.119 m^3/cap.d) about 7.7 g CH_4-COD/cap.d leaves the reactor dissolved in the effluent. In this example this amounts to 7% of the influent COD.

[72] Van Haandel and Lettinga (1994, p 120) mention a captured amount of CH_4 that corresponds to 150 MJpe/cap.yr.

(Luduvice, 2005, in: Von Sperling and Chernicharo(2005, p 1216). Weaknesses are a relatively slow start-up, a high sensitivity to inadequate operation procedures, and the requirement of frequent maintenance (cleaning of influent distribution pipes) (Florencio et al., 2001). UASB reactors require thorough preliminary elimination of non-biodegradable solids (sand, clay) which would accumulate in the reactor.

6.5.3.4 Primary treatment with Imhoff tanks

The Imhoff tank is a very reliable and flexible primary treatment technology used for solids removal by sedimentation in small-scale wastewater-management systems (Alexandre and Boutin, 1998; Sasse, 1998). The tank consists of one or two relatively small settling compartments on top of a large anaerobic sludge storage compartment. The treatment characteristics of Imhoff tanks have been described in subsection 6.3.2.4. In small-scale applications sedimentation can be also obtained by means of the non-mechanized conical Dortmund tank. The Dortmund tank requires a regular discharge of the settled primary sludge, while due to its in-built sludge storage compartment sludge removal with the Imhoff tank is much less frequent.

6.5.3.5 Secondary treatment with facultative and maturation ponds

Facultative and maturation ponds are non-mechanized technologies in which the pre-treated wastewater is purified through an enhanced self-purification process. Facultative ponds usually have an aerobic upper zone and an anaerobic zone near the bottom, maturation ponds are fully aerobic. Algae and light play a crucial role in the oxygenation in these pond types and also in the processes of pathogen die-off. The primary function of facultative ponds is a continued elimination of organic matter, while maturation ponds are laid out for advanced removal of pathogenic organisms. The die off rate of pathogens, often indicated with the first order die-off constant of faecal coliforms (K_d), is a function of temperature, alkalinity, retention time, pond depth and pond geometry. At 25^o C and a pond depth of 1 m the K_d value is in the order of 1.36 d^{-1} (Cavalcanti, 2003; Von Sperling and De Lemos Chernicharo, 2005, p 589). With decreasing pond depth the die-off constant increases, so that the required retention time diminishes, but the surface requirement stays the same. At an ambient temperature of 25 ^oC a treatment plant with 5 ponds in series and a retention time of about 16 days can achieve a faecal coliform removal efficiency of more than 4 log units (> 99.99% removal), so that an abundance of less than 1000 faecal coliforms/100 ml is reached and the effluent can be reused for unrestricted irrigation. Nitrogen is partly removed through volatilisation of ammonia, immobilization in sludge, and nitrification – denitrification (Von Sperling and De Lemos Chernicharo, 2005, p 610). Here, processes in the water and in the sediment play a role. Well-known treatment plant lay-outs are anaerobic + facultative + maturation ponds and also UASB reactor + facultative + maturation ponds are in use (Schellinkhout and Collazos, 1992; Wiegant, 2001; Aiyuk et al., 2006). In table 6.5.4 indicative values of several relevant parameters of these two trains are listed. Although UASB reactors remove organic matter more efficiently than anaerobic ponds, the overall retention time and surface requirement of chains consisting of UASB + Facultative Pond + Maturation ponds (UASB + FP + MP) and Anaerobic Pond + Facultative Pond + Maturation ponds (AP + FP + MP) are similar due to the high surface requirements for the slow pathogen die-off processes.

Strengths of pond systems are their simple construction, operation and maintenance, their reliability and flexibility and their high pathogen-removal efficiency when sufficient retention time is available. Malodour and insect problems can be prevented by avoiding growth of weeds on the pond embankment and giving wind access to the pond surface. The main weaknesses are the long hydraulic retention time and its concomitant high use of land, and the relatively high degree of water loss through evaporation which depends on ambient temperature, air humidity and the impact of the wind. The use of an UASB reactor instead of an anaerobic pond may lead to a higher organic matter removal of a pond system, but has little effect on the pathogen removal which is mainly influenced by the pond surface. The effluent of stabilization ponds usually contains high concentrations of algae, so that the overall COD removal efficiency of pond systems may be relatively low. Nevertheless, the physical quality and pathogen abundance of the effluent is radically improved.

6.5.3.6 Secondary treatment with rapid soil filtration

Under suitable conditions soil filtration can be used in the post-treatment of effluent that has undergone at least a sedimentation step. These conditions are availability of a highly permeable soil with groundwater at a sufficient depth and sufficient drainage. The relevant treatment processes are particle retention, sorption and biological conversions in the soil-water matrix. The loading of wastewater onto the soil surface occurs in an intermittent way, so that there are alternating wet and dry periods. The loading-drying cycle for maximum nitrogen removal could take 2 days of loading and 12 days of drying under summer conditions in the USA (Reed et al., 1995, p 324). Permissible hydraulic loading rates depend primarily on soil characteristics. Typical loading rates for primary effluent (BOD_5 concentrations of 150 - 200 mg/l) are 4 – 8 cm/d on a continuous basis, which corresponds to BOD_5-loading rates between 6 and 16 g BOD_5/m^2.d. No odor problems should occur at these rates (Reed et al., 1995, p 328). Under these conditions high BOD_5, N, P and Faecal Coliform (FC) removal efficiencies can be reached (table 6.5.3). As the required per capita surface is usually considerable (1.5 – 3 m^2/cap), this treatment technology is most suited to small and medium-size treatment plants at sites where the drained effluent from the infiltration basins is eventually discharged to surface water.

6.5.3.7 Secondary treatment with anaerobic upflow filtration

The anaerobic upflow filter (AUF) can be used for primary treatment of wastewater with a low suspended solids concentration and for secondary treatment after removal of the bulk of the settleable solids . In an anaerobic filter the wastewater passes a layer of carrier material in which biodegradable organic matter is retained through sedimentation and degraded through the action of an active anaerobic bacterial mass growing on and between the carrier material. The best carrier materials are plastic media that provide much space and a large surface (100 – 300 m^2/m^3) for retention of biomass and influent sludge and have a reduced risk of clogging. Alternatively many other, cheaper, packing materials (stones, cinders) could be used. Anaerobic filters are used in submerged upflow and downflow mode, where the upflow mode has a lower risk of sludge washout (Sasse, 1998). Weaknesses of anaerobic filters are the relatively low removal of nitrogen and pathogens and the possibility of clogging, so that in the case of domestic wastewater preliminary removal of the bulk of the available suspended solids is recommended. An example of such a two-step technique is the baffled anaerobic septic tank with anaerobic filter (BASTAF) (6.3.2.3).

The hydraulic retention time in an anaerobic filter may vary between 0.25 and 1.5 days with surface loading rates of less than 2.8 m/d (Polprasert and Rajput, 1982; Sasse, 1998; Morel and Diener, 2006). The BOD_5-treatment efficiency will depend on pre-treatment and on the water temperature. Two publications with a technology chain consisting of a septic tank (HRT = 2 - 3 d) and anaerobic filter (HRT = 0.5 - 1 d) working at temperatures of 20 – 30 ^{o}C report BOD_5-removal efficiencies in the range of 70 – 85% (Polprasert and Rajput, 1982; Viet et al., 2008). Community-scale application of anaerobic upflow filters has been described by Von Sperling and Chernicharo (2005, p. 728). A large scale application for 50,000 PE is reported as well (Chernicharo, 2006). It is evident that the anaerobic filter enhances the TSS and COD removal. The collection of biogas and management of malodors would require a gas-solids-liquid separator as in the case of UASB reactors. Important strengths of anaerobic filters, which make them suitable for on-site treatment of pre-treated sewage, black, brown and grey water at small and large scale, are the absence of electro-mechanical devices and consequently low energy use, and a reduced risk of sludge washout through the presence of the carrier.

6.5.3.8 Treatment with subsurface- flow constructed wetlands

Subsurface-flow constructed wetlands or planted filters are appropriate for both treatment of raw sewage (Molle et al., 2005) and post-treatment of effluents from primary treatment processes (Nyakang'o and Van Bruggen, 1999). Subsurface-flow constructed wetlands are laid out with horizontal flow and vertical down-flow.

In these planted filters wastewater is treated through separation and conversion processes taking place in the pores of a filter bed planted with helophytes like e.g. reed (*Phragmites australis*). The filter bed consists of sand, gravel and rock and is lined in order to be able to recover the effluent, avoid infiltration of groundwater and protect the surrounding soil. In *horizontal-flow planted filters* the decomposition processes are a combination of aerobic, micro-aerobic and anaerobic processes with an accent on anaerobic decomposition, while in vertical flow filters primarily an aerobic decomposition is aimed at. In *vertical-flow filters* these aerobic processes are brought about by intermittent (2 – 4 times/day) feeding of influent on top of the filter bed. In these filters air is drawn into the bed by means of the infiltrating water. By virtue of the more aerobic character of the decomposition process the treatment efficiencies of vertical-flow planted filters are higher than those of the horizontal-flow filters. The role of the plants growing on the filter bed is a supplementary supply of oxygen to the bed through the root system, stimulation of soil activity through root excretion, uptake of nutrients, reduction of effluent flow through evapo-transpiration and prevention of clogging of the bed surface through the action of wind movement on the stems (Cooper et al., 1996; Molle et al., 2005; Morel and Diener, 2006).

Horizontal- flow planted filters

Horizontal-flow planted filters are usually designed for a BOD_5 -loading rate of 6 – 10 g BOD_5/m^2.d (Morel and Diener, 2006). For the treatment of settled sewage this filter type requires 3 – 5 m^2/cap at an influent BOD_5 load of 30 g/cap.d. For grey-water treatment with a BOD_5 load after pre-treatment of 15 – 20 g BOD_5/cap.d the required filter surface is 2 – 3 m^2/capita. In the treatment of effluent of UASB-reactors fed with sewage COD loading rates of up to 13.8 g/m^2.d were applied (De Sousa et al., 2001).

The filter depth is about 0.6 m. The BOD_5 removal efficiency of a combination of a septic tank with a horizontal-flow planted filter for the treatment of mixed black and grey water is in the range of 80 – 90%. Nitrogen and phosphorus removal efficiencies are 30 – 40% and faecal coliform removal from 2 to 3 log units (99 – 99.9%) (table 6.5.4)

At treatment of UASB-effluent in a horizontal-flow constructed wetland COD, TKN, P_{tot} and FC removal efficiencies of respectively 81, 47, 64 and 99.98% were achieved at a HRT of 7 days at ambient temperatures between 19 and 33 ^oC (De Sousa et al., 2001). A strength of the horizontal-flow planted filters as compared to the vertical-flow filters is the fact that no influent pump is needed, if at least the head loss of the filter can be overcome. A drawback is the risk of clogging which leads to ponding, efficiency reduction, malodors and insect nuisance. Therefore, a prerequisite for treatment in this type of planted filter is proper pre-treatment and influent distribution, and prevention of overloading.

Vertical-flow planted filters

Vertical-flow planted filters are applied for the primary plus secondary treatment of raw sewage in small communities. Using a lay out consisting of primary and secondary filters and a total filter surface of 2 m^2/PE effluent concentrations of 60 mg/l COD, 15 mg/l SS and 8 mg/l TKN are achieved. The overall COD, SS and TKN removal efficiencies amount to about 90, 95 and 85% respectively. The COD loading rate at the primary filters amounts to 100 $g/m^2.d$ and on the combination of primary plus secondary filters 60 $g/m^2.d$ (Molle et al., 2005).

The vertical-flow planted filter for the treatment of pre-treated sewage, black and grey water is designed for a BOD_5 loading rate 10 – 20 g $BOD_5/m^2.d$, therefore slightly higher than the horizontal-flow filter. The filter depth is about 1 meter. The surface requirements are 2 –3 m^2/capita for settled sewage and 0.5 –3 m^2/capita for grey water[73]. The influent is distributed over the filter surface by means of perforated pipes laid out under the planted layer. Treatment efficiencies of vertical-flow filters are higher than of horizontal-flow filters. The BOD_5 removal efficiency is as high as 96 – 99%, the N_{tot} removal is 38 – 58%, the P_{tot} removal 40 – 58% and the FC removal 99 – 99.99 % (Haberl et al., 1995; Van Buuren et al., 1998). The intermittent loading requires dosing by means of a pump, a mechanical siphon or a tipping reservoir. The latter can be used if sufficient head is available.

Strengths of subsurface-flow constructed wetlands are the relatively simple operation and maintenance process, high efficiencies in TSS, COD, BOD_5 and pathogenic organism removal, reliability and flexibility, absence of bad smells and opportunities of combining wastewater treatment with pleasant landscaping. Drawbacks are the relatively large space requirements, high costs of construction where proper filter material is not available near the site of construction, and difficulties to restore filter bed operation once overloading and clogging problems have revealed themselves. Due to their characteristics, application of subsurface-flow constructed wetlands will be limited to areas where spatial conditions are favorable and the filter medium can be found in the vicinity. Reed and co-workers (1995, p 259) argue that the technology is probably not competitive with other treatment technologies at flow rates above 4,000 m^3/d. Despite their larger footprint and higher costs subsurface-flow constructed wetlands could be competitive with stabilization ponds in off-site applications in tropical areas, where they could be an element of a public garden area. Also combinations of planted filters (pre-treatment) and ponds (post-treatment) can be an effective treatment option.

[73] These footprint data are based on calculations by the author based on research presented by Van Buuren et al.,(1999); Cooper et al.,(1996), S.C. Reed et al.,(1995, chapter 6).

6.5.4 Mechanized treatment technologies for sewage

This subsection discusses characteristics and strength and weaknesses of the mechanized treatment technologies mentioned in table 6.5.5. The term mechanized wastewater treatment refers to the application of pumps, aerators, sludge scrapers, automatic control and monitoring equipment, etc. These mechanical devices, especially forced aeration, lead to higher conversion rates and reduction of the land requirement as compared to non-mechanized technologies. Mechanization can be less recommendable in low-income countries, as it increases the costs, the need of skilled operation and maintenance and the risks of failure, in particular where the supply of electricity is unreliable. The data in table 6.5.5 refer to applications at a capacity higher than 500 m^3/d.

6.5.4.1 Primary treatment with regular and chemically enhanced sedimentation tanks

Primary sedimentation tanks remove suspended settleable material from wastewater with the aim to reduce the organic loading rate and energy demand of the following aerobic biological treatment step. The organic sludge collected at the bottom of the tank is highly biodegradable and can be stabilized in anaerobic digesters. In this way a considerable part of the energy contained in wastewater can be recovered. Alternatively, the sludge could be dewatered and incinerated. The TSS and BOD_5 removal efficiencies in primary sedimentation tanks are about 55 % and 30 % respectively at hydraulic retention times between 1.5 and 2.5 hrs (Metcalf and Eddy Inc, 2003, p 405). The efficiency of the TSS removal can be enhanced by means of a coagulant (e.g. $FeCl_3$). This chemically enhanced primary treatment technology is able to reach a TSS and BOD removal of 60 – 80% respectively 50 - 60%. The N_{tot} and P_{tot} removal in regular sedimentation tanks are usually less than 20% as only a part of the particulates are removed. If precipitation is enhanced by means of a coagulant P_{tot} removal can be 50 – 60% (Somlyódi and Shanahan, 1998, p 26). In large-scale applications where sedimentation tanks have a flat bottom the sludge is moved to the discharge point of the tank by means of mechanically driven sludge scrapers. Strengths of mechanized primary sedimentation tanks are their relatively short retention time, their insensitivity to shock loads and small footprint. If in (sub)tropical countries a UASB reactor is used as primary treatment step, a sedimentation tank is not necessary.

6.5.4.2 Secondary treatment of sewage with suspended-growth activated sludge processes

This subsection enables comparison of three technology chains with suspended-growth treatment processes by a presentation of their characteristics. The three chains are meant for the treatment of raw and pre-settled sewage (figures 6.5.1, 2 and 3). The results are shown in table 6.5.5. In suspended-growth activated-sludge treatment organic matter and ammonium are converted to bacterial sludge and mineral end products through aerobic biological conversion. The rate of nitrification increases with increasing sludge age and hydraulic retention time. Phosphorus is to a small extent removed by incorporation into the activated sludge. Pathogens are eliminated by natural die-off and adsorption to the sludge. The developed bacteria form flocs which can be removed from wastewater through sedimentation. The process basically consists of two stages: an aeration tank for the conversion and sludge growth and a sedimentation tank for removal of the developed sludge from the treated clean effluent. Fundamental to the process are a high concentration of activated sludge in the aeration tank of 1.5 to 6 kg TSS/m^3, sufficient aeration and good mixing of influent and sludge and efficient removal of sludge in the sedimentation tank. In order to keep the sludge concentration in the aeration tank high, sludge is recirculated from the sedimentation to the aeration tank. This recirculation presupposes a good settling behaviour of the activated sludge in the secondary sedimentation tank. Though a wide range of variations of this process exists, this thesis restricts the discussion to the *completely mixed activated sludge* (CMAS) process and the *extended aeration* (EA) process (Metcalf and Eddy Inc, 2003, p 741). The oxidation ditch is a representative of the latter type of treatment process. The main differences between the two processes are the longer hydraulic retention time, lower sludge loading rate and higher sludge age of the extended aeration process. These differences lead to different qualities of the sludge and treatment efficiencies. The treatment technology to be selected depends on the type of wastewater treated and effluent quality required. In this thesis the sedimentation tank and the UASB reactor are the selected primary treatment technologies used prior to the completely mixed activated-sludge process. They form the following technology chains:

1. Bar screen + grit removal + primary sedimentation + aeration tank (CMAS) + secondary sedimentation + sludge treatment (thickeners, anaerobic digestion, sludge drying beds) (figure 6.5.1);
2. Bar screen + grit removal + equalization tank + UASB reactor + aeration tank (CMAS) + secondary sedimentation + secondary sludge treatment in UASB reactor and sludge drying beds) (figure 6.5.2).

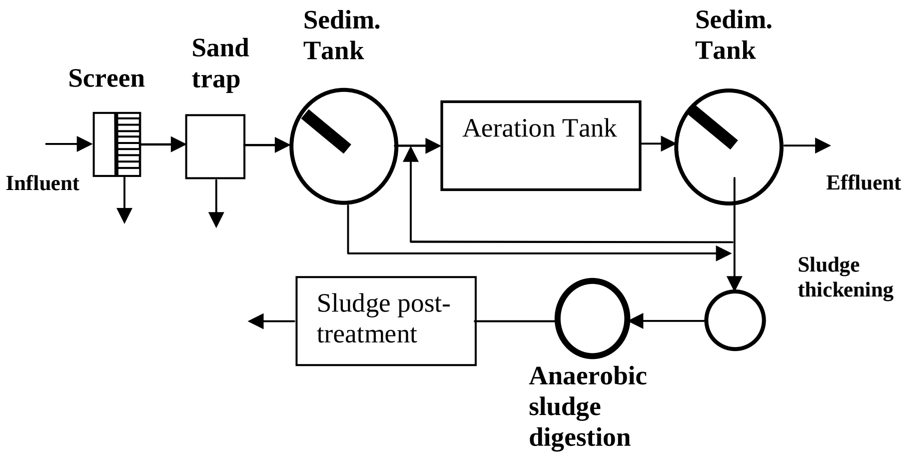

Figure 6.5.1 Lay-out of completely mixed activated-sludge sewage treatment system with anaerobic digestion of excess sludge.

These processes are selected for sewage which contains sand and degradable settleable solids. In figure 6.5.1 the highly degradable excess sludge from the activated-sludge process and the primary sludge are stabilized jointly in an anaerobic digester. Produced biogas is used for supplying a part of the energy required in the process (subsection 6.5.9.1).
If the wastewater is pre-treated in an UASB reactor (figure 6.5.2), this reactor can be used for co-treatment of excess sludge from the aerobic post-treatment process (Von Sperling and De Lemos Chernicharo, 2005, p 848). The equalization tank may be required to avoid strong influent flow and strength variations in the UASB reactor.

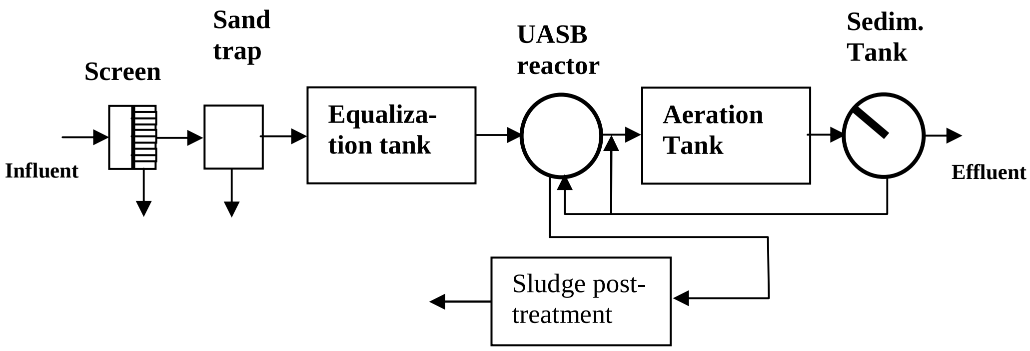

Figure 6.5.2 Lay-out of UASB pre-treatment with activated-sludge post-treatment.

Extended aeration is one of the preferred suspended-growth process for the treatment of sewage that has undergone pre-treatment by means of on-site septic tanks. This pre-treatment removes sand and a considerable part of the organic matter, so that the energy consumption and sludge production of the extended aeration process will be relatively modest. As the produced excess sludge is well stabilized due to the high sludge age in this process, the excess sludge handling can be restricted to dewatering and drying (subsection 6.5.9.2). The technology train for pre-treated wastewaters looks as follows.

3. Bar screen + grit removal + extended aeration process + secondary sedimentation + sludge treatment (sludge drying beds) (figure 6.5.3).

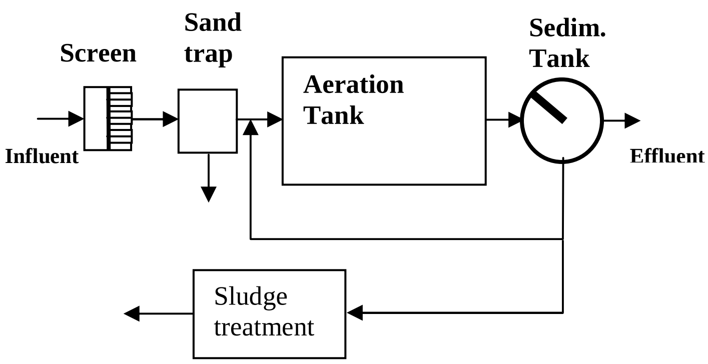

Figure 6.5.3 Lay-out of extended aeration activated sludge process for pre-settled sewage.

The screen and grit removal can be omitted if the treatment plant does not receive storm-water. This is the case where plain separate (options 6A, 7A) and plain settled separate sewer systems (options 6C-E, 7C-E) are used. A comparison of the three mentioned systems can be found in Von Sperling and Chernicharo (2005, p 850 - 853). Data from these authors, in particular the attainable treatment efficiencies, are summarized in table 6.5.5.

Strengths and weaknesses of completely mixed activated sludge and extended aeration technologies

Technologies based on the suspended-growth activated sludge process have a small footprint and achieve high treatment efficiencies in comparison with anaerobic technologies. Their main general weakness is the possibility of rising or bulking sludge in the secondary sedimentation tank which may upset the recirculation of sludge to the aeration tank and consequently the entire treatment process[74]. Bulking sludge occurs for example in situations of insufficient soluble BOD_5, low food-to-micro-organism ratios and septicity of the influent (Metcalf and Eddy Inc, 2003, p 695). At tropical temperatures nitrogen gas bubbles generated by de-nitrification in the secondary settler may cause difficulties with the sedimentation process (Von Sperling and De Lemos Chernicharo, 2005, p 852). The technology requires regular surveillance of the mechanical devices (recirculation pumps, blowers, scrapers) and proper operational skills. The extended aeration process is in some respects more simple than the completely mixed activated sludge process in that it has no primary clarifier and produces lower amounts of a more stabilized excess sludge at the cost of a longer aeration time and a higher energy consumption. The sludge from extended aeration processes requires just dewatering and drying, which is much simpler and cheaper than the full stabilization and dewatering associated with the CMAS technology. According to Von Sperling and Chernicharo (2005, p 852) the combined UASB + CMAS technology has lower excess sludge production, a better sludge dewaterability and lower energy requirement and footprint than the primary sedimentation (SED) + CMAS and extended aeration technologies. None of the technology chains presented in figures 6.5.1 to 6.5.3 delivers an effluent that can be reused for unrestricted irrigation in agriculture without further disinfection.

6.5.4.3 Secondary treatment sewage with aerobic biofilm technologies

The conversion of substrate in aerobic attached-growth or biofilm technologies is brought about by biological sludge attached to a carrier material. The fixation of the activated sludge to the carrier material eliminates the need of secondary-sludge recirculation and avoids bulking-sludge problems associated with suspended-growth processes. In this subsection the following attached-growth technologies are presented:

- Trickling filters (TF);
- Submerged aerated fixed-film reactor (SAF);
- Mobile-bed bioreactors (MBBR);
- Rotating Biological Contactor (RBC);
- Downflow hanging sponges towers (DHS).

In trickling filters (TF) and down-flow hanging sponges towers (DHS) the wastewater is distributed over the top of a tank or tower filled with carrier material and coming in contact with the biofilm and oxygen on its way to the bottom of the reactor. Air enters through the channels inside the carrier material. In submerged aerated fixed-film reactors (SAF) and mobile-bed bioreactors (MBBR) the carrier material remains submerged in the wastewater and oxygen is supplied by diffusers. In rotating biological contactors (RBC) a mechanically

[74] Small suspended-growth activated sludge treatment plants in Vietnam showed invariably very low mixed liquor suspended solids concentrations (chapter 9 of this thesis).

driven rotating cage filled with carrier material or sets of disks provide alternating contact of the biofilm with wastewater and with air. The rotating biological contactor is most appropriate for small wastewater-treatment stations, due to the characteristics of its construction. A detailed classification of attached-growth technologies is presented by Von Sperling and Chernicharo (2005, part 6).

These attached-growth technologies can be applied as the biological treatment step for settled sewage and for post-treatment of septic-tank or UASB effluent. The combination of pre-treatment in a UASB reactor and post-treatment with an attached-growth process has the advantages of biogas production, lower energy consumption and a simpler excess sludge treatment (Chernicharo, 2006). The excess sludge that leaves the attached-growth process is retained in the secondary sedimentation tank and recirculated to the UASB reactor for further stabilization (figure 6.5.4).

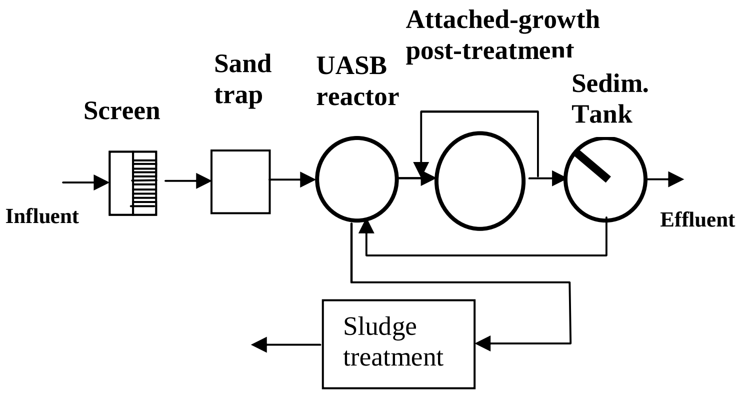

Figure 6.5.4 Lay-out of UASB pre-treatment with aerobic attached growth post-treatment

In all technologies excess sludge from the UASB reactor is thickened and further stabilized on sludge drying beds. Similar to the suspended growth activated sludge processes the attached-growth post-treatment technologies can be dimensioned to attain a high degree of nitrification through reduced organic (COD, BOD_5) sludge loading rates. In the examples detailed in table 6.5.5 the *volumetric* organic sludge loading rates in the attached-growth stage of the UASB-TF, UASB-SAF, UASB-MBBR and UASB-DHS are 0.20, 0.28, 0.30 and 0.72 kg $BOD_5.m^{-3}.d^{-1}$ respectively. For the UASB-SAF and UASB-MBBR with a specific surface of the plastic carrier of 250 m^2/m^3 the *surface* organic loading rates were 1.25 and 1.67 g $BOD_5.m^{-2}.d^{-1}$ and the surface TKN loading rates of 0.75 and 1.0 g $BOD_5.m^{-2}.d^{-1}$ respectively. These four UASB-aerobic post-treatment systems all may attain a BOD_5 treatment efficiency in the range of 85 to more than 90% and a high degree of nitrification. Few data were found about N_{tot} and P_{tot} removal. According to Chernicharo N_{tot} removal efficiencies of UASB + attached growth post-treatment systems are 60% at most and P_{tot} removal is lower than 35%. The nitrogen removal is caused by uptake in the surplus sludge and a de-nitrification in anoxic zones within the biofilms on the carrier material (Chernicharo, 2006).

Strenghts and weaknesses of attached-growth secondary treatment technologies

Strengths claimed for the aerobic attached-growth technologies are among others: high biomass concentrations in the aeration tank, low excess sludge production, effectiveness for dilute wastewaters and resistance to shock loads (Metcalf and Eddy Inc, 2003, p 957; Gonçalves, 2005). The conversion processes may be severely constrained if biofilm detachment and growth are not balanced and clogging of the carrier material results. This problem does not occur in the mobile-bed bioreactor. There, collisions of the moving carrier pellets provide abrasion of the excess sludge, leading to improved mass transfer and accelerated biochemical reactions at the carrier/biofilm surface and prevention of clogging (Lazarova and Manem, 1994; Daude and Stephenson, 2003; Ødegaard, 2005). In a comparative study of municipal sewage treatment the excess-sludge production rate of the activated-sludge process proved to be 0.88 kg TSS/kg COD_{rem}, while it was only 0.06 kg TS/kg COD_{rem} in case of the UASB-downflow hanging sponges system. The temperatures during this study varied between 9 and 32 ^{o}C. In addition did the sludge stabilization in the UASB-DHS system prove so effective that further stabilization was unnecessary (Tandukar et al., 2007). The DHS technology used in post-treatment of UASB effluent has a remarkably high performance (e.g. a faecal coliform removal efficiency of 3 to 4 log units) at a relatively low retention time (2 to 4 hrs in the DHS stage) (Tandukar et al., 2007; Tawfik et al., 2008). This is probably due a combination of plug flow, high oxygen concentration and high surface area of the polyurethane sponge material with its concomitant high volumetric sludge concentration. Consequently, in UASB-attached-growth reactor systems the DHS technology could lead to a significantly lower footprint (0.08 m^2/capita) than the other attached-growth technologies (0.12 – 0.14 m^2/capita). The energy requirement of the UASB - downflow hanging sponges system is lower. The faecal coliform treatment efficiencies reported by Tawfik and co-workers (2008) and Tandukar and co-workers (2007) lead to effluents that reach or nearly reach the requirement for irrigation water of crops that are normally eaten raw (required FC abundance < 1000/100 ml (WHO, 2006). Attainment of this requirement in a consistent way at a total hydraulic retention time of about 12 hours would be not less than a break-through in sewage treatment for effluent reuse.

Table 6.5.3 Indicative values of performance of small-scale non-mechanized off-site treatment options for sewage applicable at flow-rates < 500 m^3/d.

(IMH = Imhoff tank; FP = facultative pond; AUF = anaerobic upflow filter; RSF = rapid soil filtration; HFRB = horizontal-flow reed bed filter; VFRB = vertical-flow reed bed filter; SDB = sludge drying bed)

	Unit	Primary		Primary and secondary			
		IMH	FP	IMH+AUF	IMH+RSF	IMH+HFRB	IMH+VFRB
Reference		[75]	[76]	[77]	[78]	[79]	
HRT_{tot}	Day	0.6	15	1.1	0.6	25	20
Area required[80]	m^2/cap	0.07	1.6	0.17	2.7[81]	3.9[82]	3.2[83]
Removal							
BOD_5	%	25-35	75 - 85	70 – 85	n.a.	80 - 90	96 - 99
N_{tot}	%	0-25	n.a.	10 – 25	~80	30 - 40	35 – 58
P_{tot}	%	10-20	n.a.	10 – 20	> 95	30 - 40	40 – 58
FC	%	< 90	< 90	< 90	n.a.	99 – 99.9	99 – 99.99
Sludge accum[n]	kg TSS/cap. yr	5.3	Very small	8.1	5.3	5.3	5.3
Excess sludge treatment		SDB	SDB	SDB	SDB	SDB	SDB
Strengths		Robust; Compact; Low maintenance requirement	Moderate BOD_5 removal efficiency; Low maintenance requirement	Robust; Low maintenance requirement	Low maintenance requirement; Potential of high N removal	Low maintenance requirement; Good BOD_5 removal efficiency	Low maintenance requirement; Very good treatment efficiency
Weaknesses		Low treatment efficiency	High land requirement; Loss of water through evaporation; Risk of malodors	Moderate treatment efficiency	High land requirement; Intermittent dosing of wastewater on RSF surface	Very high land requirement; Risk of clogging of HFRB	High land requirement; Intermittent dosing of wastewater on VFRB surface

75 (Sasse, 1998, chapter 9).
76 (Arthur, 1983; Pena Varon and Mara, 2004).
77 (Von Sperling and De Lemos Chernicharo, 2005, chapter 27).
78 (Reed et al., 1995, p 321).
79 (Cooper et al., 1996; Morel and Diener, 2006).
80 All area calculations include drying beds for sludge, but no zone margins.
81 Rapid soil infiltration area hydraulic design rate: 0.06 $m^3.m^{-2}.d^{-1}$ (continuous basis).
82 HRT calculated for the empty HFRB bed; HFRB design loading rate: 8 g BOD_5 $.m^{-2}.d^{-1}$.
83 HRT calculated for the empty VFRB bed; VFRB design loading rate: 10 g $BOD_5.m^{-2}.d^{-1}$.

Table 6.5.4 Indicative values of performance of non-mechanized off-site treatment options for sewage that are applicable at flow-rates > 100 m^3/d.

(AP = anaerobic pond; UASB = upflow anaerobic sludge blanket reactor; FP = facultative pond; MP = maturation pond; HFRB = horizontal-flow reed bed filter; VFRB = vertical-flow reed bed filter; TH = sludge thickener; SDB = sludge drying bed)

	Unit	Primary		Primary and secondary			
		AP	UASB	AP + FP + MP	UASB + FP + MP	UASB + HFRB	UASB + VFRB
Reference		[84]	[85]	[86]	[87]	[88]	[89]
HRT_{tot}	day	2	0.25 – 0.4	19.8	14.2	11.8	9.7
Area required	M^2/cap	0.16	0.10	3.1	2.8	1.93	1.60
Removal							
BOD_5	%	40 – 60	65 – 85	90 - 95	90 – 95	87 - 93	95 - 99
N_{tot}	%	n.a.	5 – 25	30 – 60	30 – 60	30 – 40	38 – 58
P_{tot}	%	n.a.	0 – 20	30 – 60	30 – 60	30 – 40	40 – 58
FC	%	90 – 95	60 – 90	99.99	99.99	99 – 99.9	99 – 99.99
Excess sludge treatment		TH + SDB	TH + SDB	TH + SDB	TH + SDB	TH + SDB	TH + SDB
Strengths		Low maintenance requirements	Low sludge production; Low footprint; Utilizable biogas	Low maintenance requirements; Unrestricted irrigation	High effluent quality; Low maintenance skills; Unrestricted irrigation	High effluent quality; Low maintenance skills	High effluent quality; Low maintenance skills
Weaknesses		Malodors; Methane emissions	Frequent maintenance	Large land requirement; Methane emissions	High land requirement; Frequent maintenance	High land requirement; Frequent maintenance; Filter bed clogging; Filter material requirement	High land requirement; Frequent maintenance; Filter material requirement

[84] (Arthur, 1983; Pena Varon and Mara, 2004; Von Sperling and De Lemos Chernicharo, 2005, chapters 12 and 14).
[85] (Van Haandel and G. Lettinga, 1994; Von Sperling and De Lemos Chernicharo, 2005, p 740).
[86] (Arthur, 1983; Pena Varon and Mara, 2004; Von Sperling and De Lemos Chernicharo, 2005, chapters 12 and 14).
[87] (Van Haandel and G. Lettinga, 1994; Von Sperling and De Lemos Chernicharo, 2005, chapters 27.2, 14 and 17; Chernicharo, 2006).
[88] (Haberl et al., 1995; Cooper et al., 1996; De Sousa et al., 2001; Von Sperling and De Lemos Chernicharo, 2005, p 740).
[89] (Haberl et al., 1995; Cooper et al., 1996; Van Buuren et al., 1998; Von Sperling and De Lemos Chernicharo, 2005, p 740).

Table 6.5.5 Indicative values of performance of mechanized treatment options for sewage (Q > 500 m^3/d).
(SED = sedimentation tank; CEPT= chemically enhanced primary treatment; UASB = Upflow Anaerobic Sludge Blanket; AS = activated sludge; EXT AER = extended aeration; TF = trickling filter; SAF = submerged aerated filter; MBBR = mobile-bed bioreactor; DHS = down-flow hanging sponges; AD = anaerobic digester; DEW = dewatering)

	Unit	Primary		Primary and secondary						
		SED	CEPT	SED + AS	UASB + AS	EXT AER	UASB + TF	UASB + SAF	UASB + MBBR	UASB + DHS
Reference		[90]	[91]	[92]			[93]	[94]	[95]	[96]
HRT_{tot}	Days	0.06 – 0.10	0.06 – 0.10	0.34	0.4 – 0.6	1.77	0.5 – 0.8	0.6 – 0.7	0.6 – 0.7	0.3 – 0.7
Carrier material biofilm reactor		-	-	-	-	-	Stones or plastic	Plastic 250 m^2/m^3	Plastic 250 m^2/m^3	Polyurethane sponge
Energy consumption	MJpe/ cap/yr	Low	Low	65 - 94	50 – 72	72 – 126	Low	Low	Low	0
Area required	M^2/cap	0.05 – 0.1	0.05 – 0.1	0.16 – 0.3	0.2 – 0.3	0.34	0.12 – 0.15	0.12 – 0.15	0.12 – 0.15	0.08
Removal										
TSS	%	<60	<80	90 - 95	87 - 93	90 - 95	87 - 93	87 - 93	87 - 93	n.a.
BOD_5	%	30	50 – 60	85 – 95	85 – 95	93 – 98	83 – 93	83 – 93	90 - 95	90 – 95
NH_4^+	%	Low	Low	85 – 95	83 – 90	90 – 95	50 – 85	50 – 85	<90	60
N_{tot}	%	Low	Low	25 – 30	15 - 25	15 – 25	< 60	< 60	<60	56
P_{tot}	%	Low	50 – 60	25 – 30	10 – 20	10 – 20	< 35	< 35	<35	n.a.
FC	%	Low	low	90 - 99	90 - 99	90 – 99	90 - 99	90 - 99	90 - 99	99.0 - 99.99
Excess sludge treatment		AD + DEW	AD + DEW	AD + DEW	DEW	DEW	DEW	DEW	DEW	DEW

[90] (Metcalf and Eddy Inc, 2003, p 405).
[91] (Somlyódi and Shanahan, 1998, p 26).
[92] (Von Sperling and De Lemos Chernicharo, 2005, chapter 30). The data about application of activated sludge and extended aeration plants are from this chapter.
[93] (Elmitwalli et al., 2003; Von Sperling and De Lemos Chernicharo, 2005, chapters 27.2 and 43).
[94] (Gonçalves et al., 1998; Canziani et al., 1999; Von Sperling and De Lemos Chernicharo, 2005 chapters 27.2 and 45).
[95] (Ødegaard, 2005; Von Sperling and De Lemos Chernicharo, 2005, chapter 27.2; Chernicharo, 2006).
[96] (Uemura et al., 2002; Tandukar et al., 2007; Tawfik et al., 2008).

Table 6.5.5 (continued) Indicative values of performance of mechanized treatment options for sewage (Q > 500 m^3/d).
(SED = sedimentation tank; CEPT= chemically enhanced primary treatment; UASB = Upflow Anaerobic Sludge Blanket; AS = activated sludge; EXT AER = extended aeration; TF = trickling filter; SAF = submerged aerated filter; MBBR = mobile-bed bioreactor; DHS = down-flow hanging sponges; AD = anaerobic digester; DEW = dewatering)

	SED	CEPT	SED + AS	UASB + AS	EXT AER	UASB + TF	UASB + SAF	UASB + MBBR	UASB + DHS
Strengths	Small footprint	Small footprint; P-removal	High treatment efficiency	High treatment efficiency	Very high treatment efficiency; Stable sludge	Simple operation; Low energy requirement	Simple operation	No clogging of carrier	Low energy Low sludge prod^n; High FC rem. eff.
Weaknesses	Low treatment efficiency; Putrescible sludge	Dosage of coagulant; Putrescible sludge	High energy consump^n; High sludge prod^n; Skilled O&M	Skilled O& M	High energy consump^n; Large footprint; Skilled O&M	Skilled O& M	Skilled O& M; Risk of clogging	Skilled O& M; Expensive carrier material	Frequent maintenance

6.5.5 Selection of sewage-treatment systems

In the previous subsections non-mechanized (6.5.3) and mechanized (6.5.4) sewage-treatment technologies were introduced. The aim of this subsection is to enable the selection of feasible treatment options in a situation under study. This is done by making an assessment of the mentioned technologies with respect to restrictive factors and a visual representation in screening aids. With respect to the treatment a distinction is made between *raw sewage* and *sewage that has been pre-treated or that is very diluted*. This distinction is relevant as pre-treated and diluted sewage contains low amounts of suspended solids and/or organic matter, so that the primary sedimentation stage can be omitted. Low influent organic matter concentrations would also reduce the utility of UASB reactors. Tables 6.5.6.A and 6.5.6.B present the restrictions of the various technologies and figures 6.5.5.A and 6.5.5.B the corresponding screening aids.

The screening aids of figures 6.5.5.A and 6.5.5.B are based on the assumptions:

1. Minimum water temperatures of less than 20^{o}C which occur outside the tropical climate zone preclude the use of UASB reactors and upflow anaerobic filters, because their efficiency decreases much at lower temperatures. The most likely methods at low minimum temperatures are mechanized aerobic treatment methods, though stabilization ponds and planted filters are feasible as well if sufficient land is available;
2. A lack of skilled surveillance, regular power supply and spare parts render mechanized technologies unfeasible and lead to the requirement of non-mechanized methods, such as UASB reactors, ponds, soil infiltration and wetlands;
3. Where frequent basic maintenance is not warranted the UASB technology is precluded and only very robust technologies, like Imhoff tanks, upflow anaerobic filters, ponds and wetlands are feasible;
4. If flat land is scarce and irregularities occur in the supply of power, spare parts and frequent basic maintenance, only simple, very robust and compact technologies like Imhoff tanks and upflow anaerobic filters are feasible. The treatment efficiencies of these technologies do not reach the secondary treatment level. The mentioned compact, and simple, technologies are suitable only for small-scale installations;
5. Where flat land is available, but an affordable medium for use as a filter material is not available subsurface-flow wetlands (horizontal or vertical-flow planted filters) are unfeasible;
6. Rapid soil infiltration is considered a technology that requires the availability of frequent basic maintenance in order to guarantee an appropriate loading rate to the soil. Where flat land is available, but the soil is impermeable or has a high water table rapid soil infiltration can not be applied.

The screening aid focuses at warm climate zones and small-communities. Several treatment options (Imhoff tanks, anaerobic upflow filters, constructed wetlands) would not be eligible at a scale larger than 500 m^3/d (table 6.5.2). An overview of performance data of the treatment technologies for sewage is presented in tables 6.5.3 until 6.5.5.

Table 6.5.6.A Screening matrix for primary plus secondary off-site treatment technologies for raw sewage (COD_{inf} > 400 mg/l).
(+ feasible; - unfeasible; X = factor irrelevant to technology)

Technologies / Restrictive factors	Non-mechanized technologies								Mechanized technologies				
	IMH + UAF	IMH + Ponds	IMH + HFRB	IMH + VFRB	IMH + RSF	UASB + FP + MP	UASB + HFRB	UASB + VFRB	SED + CMAS	EXT AER	SED+ TF/ SAF	UASB + CMAS	UASB + TF/SAF
Temperature < 20° C	-	+	+	+	+	-	-	-	+	+	+	-	-
Lack of skilled surveillance, power and spare parts not warranted	+	+	+	+	+	+	+	-	-	-	-	-	-
Limited availability of regular basic maintenance	+	+	+	+	-	-	-	-	-	-	-	-	-
Limited availability flat land	+	-	-	-	-	-	+	+	+	+	+	+	+
Unavailability of affordable filter medium	X	X	-	-	X	X	-	-	X	X	X	X	X
Unavailability of permeable soil and a low water table	X	X	X	X	-	X	X	X	X	X	X	X	X

Table 6.5.6.B Screening matrix off-site secondary treatment technologies for pre-settled and diluted raw sewage (COD_{inf} < 200 mg/l).
(+ feasible; - unfeasible; X = factor irrelevant to technology)

Technologies / Restrictive factors	Non-mechanized technologies					Mechanized technologies			
	UAF	AP + FP	HFRB	VFRB	RSF	CMAS	EXT AER	TF	SAF
Temperature < 20^{o} C	-	+	+	+	+	+	+	+	+
Lack of skilled surveillance, power and spare parts not warranted	+	+	+	+	+	-	-	-	-
Limited availability of regular basic maintenance	+	+	+	-	-	-	-	-	-
Limited availability flat land	+	-	-	-	-	+	+	+	+
Unavailability of affordable filter medium	X	X	-	-	X	X	X	X	X
Unavailability of permeable soil and a low water table	X	X	X	X	-	X	X	X	X

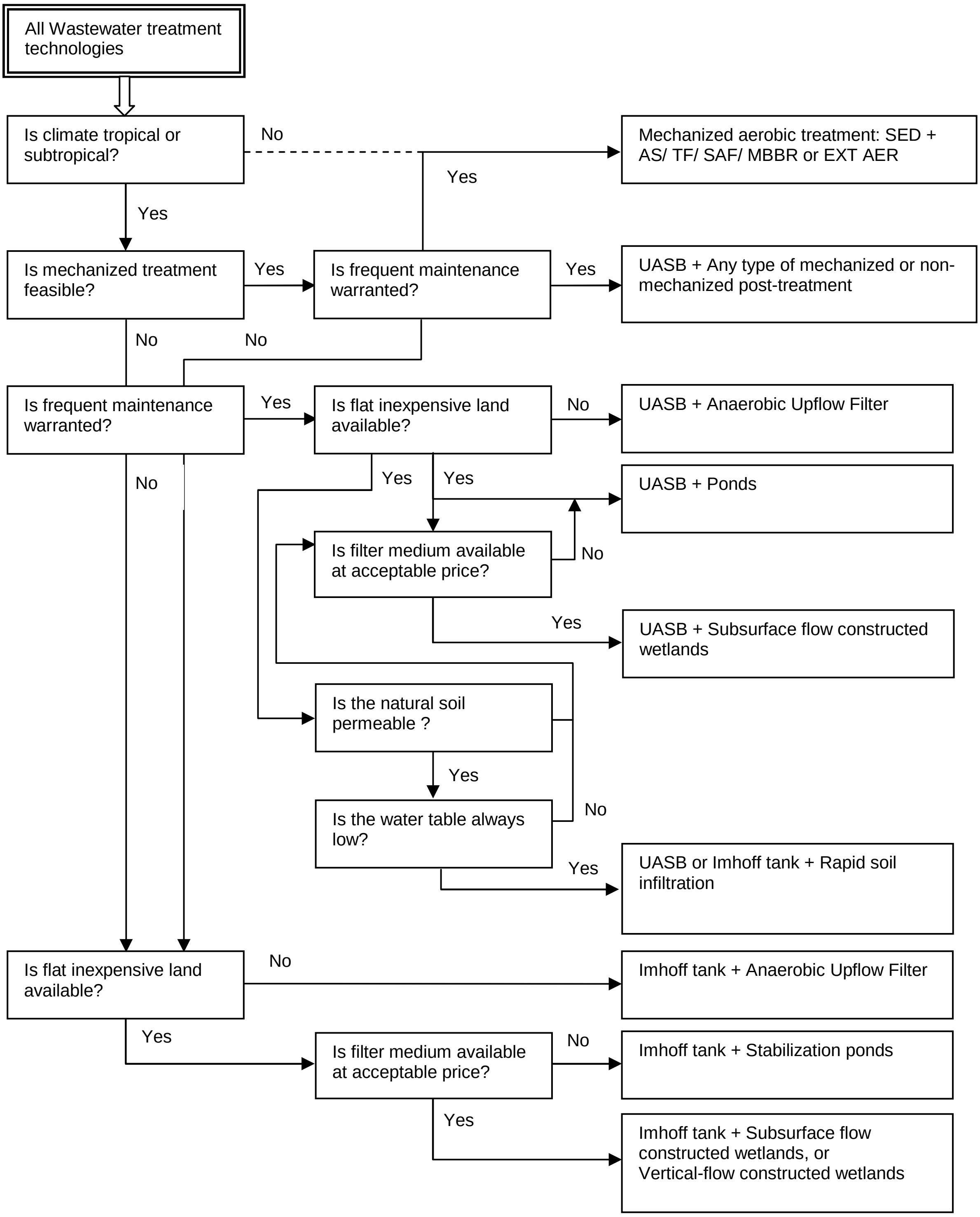

Figure 6.5.5.A Screening aid for community-scale sewage treatment in warm climates. *(COD_{inf} $\geq$ 200 mg/l, for primary plus secondary technologies in the capacity range of approximately 100 to 500 m^3/day)*

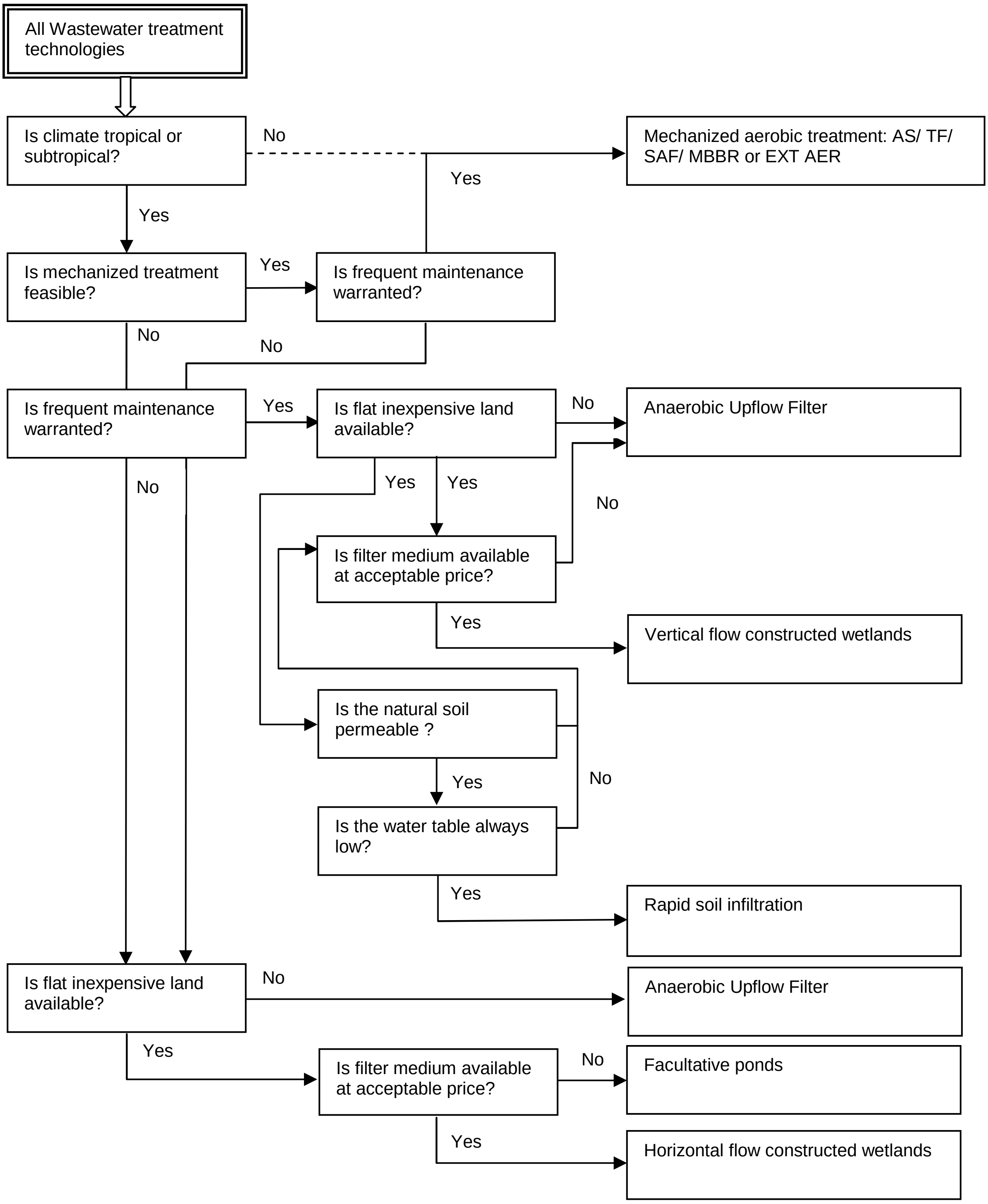

Figure 6.5.5.B Screening aid for community-scale treatment of diluted sewage in warm climates. *(COD_{inf} < 200 mg/l; for secondary technologies in the capacity range of approximately 100 to 500 m^3/day)*

6.5.6 Treatment of concentrated black water collected by means of a vacuum system

Conventional off-site sanitation systems with flush toilets, sewerage and end-of-pipe sewage treatment have been criticized for their high costs, high water consumption, relatively high output of pollutants and limited recovery of useful by-products (Cairncross and Feachem, 1983, p. 110; Lettinga et al., 2001). Recently, new systems have been developed based on *vacuum toilets*, which use very little flush water, and separated collection and treatment of concentrated black and grey water. These are the systems of group 9 and 11 in chapter 5. The collection and treatment facilities are thought to serve communities rather than cities. The aim of this approach is to use less resources and better enable reuse of valuable components (energy, nutrients, biosolids) of wastewater than the flush toilet based system. Whether this is the case remains to be proven. The outcome could be dependent on local circumstances.
The concept was introduced in the literature by Otterpohl and co-workers in 1997 aiming at decentralized treatment in Germany (Otterpohl et al., 1997; Oldenburg et al., 2008). The concentrated black water would be treated in an anaerobic digester working in the mesophilic or thermophilic temperature range. The digester delivers biogas and digestate (mixture of sludge and water). The low per capita influent volume (use of vacuum toilets) and high concentration of organic matter enable to obtain a net positive energy output, despite the possible need to heat the wastewater for anaerobic treatment in moderate and cold climates. The digestate which contains all nutrients and part of the organic matter could be used as soil conditioner on agricultural land. Advantages of this technology are its simple flow sheet (one treatment stage followed by transport) and full recovery of nutrients from black water (N and P). Drawbacks are the potential presence of pathogenic organisms and relatively high concentrations of hazardous substances, such as residues from pharmaceuticals, in the digestate, and the transport of the digestate (approximately 1.9 m^3/cap.yr , see subsection 6.3.3.2). This option would be economically feasible where the digestate could be applied to land in the vicinity of the source.

In several countries agricultural reuse of sludge derived from municipal-wastewater, as envisaged in the lay-out elaborated by Otterpohl and co-workers, is not allowed as the risks of soil contamination are deemed unacceptable. Accordingly, other methods to recover useful substances from concentrated black water are being researched. An approach reported here is a sanitation chain consisting of vacuum-toilets, vacuum transport, UASB reactor (methane recovery), struvite precipitator (P-recovery) and OLAND reactor (N-removal) (figure 6.5.7).

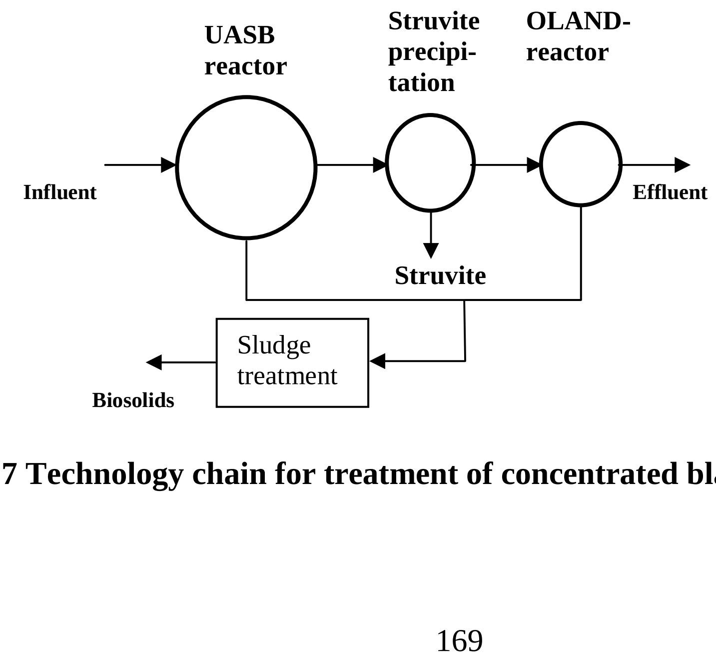

Figure 6.5.7 Technology chain for treatment of concentrated black water.

In order to increase the methane yield from the UASB reactor also biodegradable kitchen waste can be added to the black water. In this section the conversions in the three stages are analyzed, and summarized in tables 6.5.7 and 6.5.8. The description of this system is based on several recent publications (Kujawa, 2005; Meulman et al., 2008; Zeeman et al., 2008; De Graaff, 2010). Another technology chain suggested for the treatment of concentrated black water could consist of an UASB reactor followed by iron-phosphate precipitation and separation, OLAND reactor for nitrogen removal and a denitrifying sand filter with dosage of an electron-donor (Wiegant, 2007, p 5). That chain is not discussed here.

Concentrated black water (collection with vacuum toilets)
According to the data presented in chapter 5 the loads of COD, N and P in domestic black water are respectively 57, 12.5 and 1.5 g/cap.d. Through the use of vacuum toilets the flow of black water is reduced from 30 – 45 to approximately 7 l/cap.d. At a black water COD flux of 57 g COD/cap.d the COD influent concentration is about 8 g/l. The N and P concentrations in the concentrated black water are respectively 1.79 and 0.21 g/l. Complete methanation of the influent COD would yield 14.2 g CH_4/cap.d. Where kitchen waste is added (200 g wet weight/cap.d, 60 g COD/cap.d), the COD influent concentration is about 17 g/l and the methane yield at complete methanation 29.2 g CH_4/cap.d.

UASB reactor
In initial experiments a UASB septic tank was used for the treatment of concentrated black water at 25 ^oC. A COD_{tot} removal of 78% was obtained at an HRT of 29 days (Kujawa, 2005; Kujawa-Roeleveld et al., 2006). Research with a lab-scale UASB reactor demonstrated that the hydraulic retention time can be reduced to about 9 days without diminishing the removal efficiency (De Graaff, 2010, p 49). In pilot-scale UASB reactors working at temperatures of 25 to 35 ^oC and with an hydraulic retention time of about 30 days about 85% of incoming COD is converted to methane (about 60%) and sludge (about 25%). About 15% of the influent COD stays in the effluent (Meulman, 2008) [97]. The nitrogen removal is small (5 – 10%) and a part of the phosphate is removed from the liquid phase through retention in the sludge. In practice about 50% of the incoming phosphate, equivalent to 0.27 kg/cap.yr, is removed in the UASB septic tank (Kujawa, pers. comm. 2008)[98]. If the influent is concentrated black water (COD load = 57 g COD/cap.d), the temperature 25^o C and the methanation rate 60%, the methane production is in the order of 8.5 g CH_4/cap.d. The gross heat value of this methane would be 156 MJpe/cap.yr[99]. Where kitchen waste is added, the methane production would increase to 17.6 g CH_4/cap.d ((57 + 60)*0.6*0.25 = 17.6 g CH_4/cap.d), equivalent to 324 MJpe/cap.yr. This source of energy could be utilized to run the black-water treatment plant and obtain some excess. In temperate climates UASB reactors have to be heated. The heat required in the case of a reactor for mixed concentrated black water and kitchen waste running at 35^o C is estimated at 66 MJth/cap.yr and the electric

[97] Preliminary data from Meulman (2008) showed a methanation efficiency of about 75% at 35 ^oC. With an UASB septic tank (HRT = 30 days) working at a temperature of 25 ^oC the following distribution of influent COD was found: sludge about 15%, captured methane about 25%, effluent 20 – 25% leaving an unexplained COD loss of about 40% (Kujawa, 2005, p 65). If it is assumed that the 40% of the influent COD missing in the COD balance is in fact methane gas, the total methanation efficiency would be about 60% (Kujawa, 2005, chapter 5).
[98] De Graaff (2010, p 52) found 40% P removal in the UASB reactor.
[99] The heat value of methane gas is 50.4 KJ/g CH_4. Therefore the heat value of the produced methane gas from black water is: 8.5 * 365 * 0.0504 = 156 MJpe/cap.yr.

energy for the stirrers of the UASB reactor amounts to 18 MJe/cap.yr (table 6.5.7). These energy consumption data need further confirmation (Meulman, 2008).

Struvite precipitator

The struvite precipitation aims at phosphate removal through precipitation of magnesium-ammonium-phosphate (MAP = $MgNH_4PO_4.6H_2O$). The struvite precipitator is a small unit in the treatment chain as its HRT is short (about 0.5 hr). The formation of this salt requires addition of a Mg-compound (MgO, $Mg(OH)_2$) and NaOH for pH adjustment to about pH 9. The phosphate recovery from black water is estimated at 0.14 kg P/cap.yr (Zeeman et al., 2008), which is about 25% of the total phosphate available in black water (0.55 kg P/cap.yr). If kitchen refuse is added to the black water the phosphate recovery could be slightly higher, though only little phosphate in kitchen refuse is present in the soluble form. Only a minute fraction of the available NH_4^+ is removed (14 g N per 31 g P) with the MAP precipitate, unless much extra soluble phosphate is added. Without such addition the precipitation of ammonium would amount to 0.063 kg N/cap.yr, which is only 1.4 % of the influent N_{tot}.

OLAND reactor

The OLAND process is a combination of the aerobic biological conversion of ammonia to nitrite and anaerobic conversion of ammonia and nitrite to nitrogen gas (Annamox - process). These processes can be realized jointly in a reactor type in which aerobic and anaerobic conditions coexist, such as a rotating biological contactor (RBC) (Windey et al., 2005), or in a two-step process(De Graaff, 2010). Stable removal of 85% of the nitrogen proved possible by means of an Annamox reactor with pH control at 25 ^oC. Addition of calcium was required in order to stimulate the formation of annamox granules with high settling velocity, so that biomass could be retained well in the reactor (De Graaff, 2010, chapter 4). The energy consumption of the OLAND process used for pre-treated blackwater and kitchen refuse is estimated to be in the order of 16 MJe/cap.yr (Meulman, 2008).

Performance of the chain

Characteristics and performance data of the treatment chain for concentrated black water as detailed above are presented in tables 6.5.7 and 6.5.8.

Table 6.5.7 Characteristics and indicative treatment efficiencies of a black-water/kitchen refuse treatment plant consisting of UASB reactor, struvite precipitator and OLAND reactor working at 25 ^{o}C (based on Meulman(2008)).

	Unit	UASB reactor	Struvite precipitation	OLAND reactor	Total
HRT_{tot}	d	9	0.021	3.75	13
Energy	MJth/cap.yr	66	0	n.a.	66
consumption	MJe/cap.yr	18	27	16	61
Energy prod.	MJpe/cap.yr	324	0	0	324
Area required	m^2/cap				0.22
Removal efficiencies					
COD	%	85	0	0	85
NH_4^+	%	0	1	89	90
N_{tot}	%	5	1	80	86
P_{sol}	%	n.a.[100]	100	0	100
P_{tot}	%	50	25	0	75

The total HRT of the three–stage black-water/kitchen refuse treatment technology chain consisting of UASB reactor- struvite precipitation unit – OLAND reactor would be in the range of 11 – 13 days (Meulman et al., 2008; Zeeman et al., 2008). The area required is 0.22 m^2/cap. The total COD removal of the process is in the order of 85% and could yield a gross heat value of 324 MJpe/cap.yr through anaerobic conversion to biogas. The energy consumption of this treatment system (not including the grey water system) could include the heating of the UASB and the OLAND reactor and the operation of wastewater pumps, dosing pumps and stirrers. Using the data presented in table 6.5.7 it is calculated that the indicated treatment chain for concentrated black water and kitchen refuse feeding a combined heat and power plant with an efficiency of 33% could produce about 108 MJe/cap.yr and 216 MJth/cap.yr (total 324 MJpe/cap.yr). Using the tentative data given by Meulman the energy consumption would be 61 MJe/cap.yr and 66 MJth/cap.yr, yielding a surplus of 108 – 61 = 47 MJe/cap.yr (= 1.5 W/cap) and a surplus of thermal energy of 216 – 66 = 150 MJth/cap.yr.

According to another estimation a sanitation system with separate treatment of black and grey water and methane recovery from black and grey water could save 200 MJpe/cap.yr in comparison with a conventional gravity sewer-based sanitation system (Zeeman et al., 2008). This amount of 200 MJpe/cap.yr could be transformed to about 65 MJe/cap.yr and 135 MJth/cap.yr. Apparently, the surplus of electrical energy in the estimation made by Zeeman is slightly higher which could be attributed to the additional biogas recovered by anaerobic treatment of grey water.

Fate of nutrients

In addition to energy also nutrient recovery is an important driver for the development of innovative sanitation systems. The total amount of nitrogen and phosphorus discharged in black water (without kitchen refuse) amounts to 4.56 kg N/cap.yr and 0.55 kg/cap.yr

[100] Soluble phosphate could be removed in the UASB reactor by precipitation as an insoluble salt. As this kind of removal is not measured independently, the removal by precipitation in incorporated in the removal of $P_{tot.}$

respectively (chapter 5, table 5.2). Taking into account the overall removal percentages of the concentrated black water treatment system, the amount of COD, N and P recovered and discharged are as presented in table 6.5.8.

Table 6.5.8 Material balance of three-stage concentrated black-water treatment chain

	Influent	Effluent		Recovered		Rest (to sludge/ atmosphere)	
	Kg/cap.yr	%	Kg/cap.yr	%	Kg/cap.yr	%	Kg/cap.yr
COD	20.8[101]	15	3.12	60[102]	12.5	25	5.18
N_{tot}	4.56	14	0.64	1	0.046	85	3.87
P_{tot}	0.55	25	0.14	25	0.14	50	0.27

The typical *overall* removal percentages of COD, N and P are respectively 85, 86 and 75% (table 6.5.7). The effluent of this technology chain does not meet effluent discharge requirements, particularly as the COD concentration is still in the range of 1 – 4.2 g/l dependent on the type of influent and process temperature (Kujawa-Roeleveld et al., 2006; Meulman et al., 2008) . In addition, the concentrations of residual micro-pollutants, such as rests of pharmaceutical products, and the abundance of faecal microorganisms could be high. The required further treatment could be realized by means of aerobic treatment and/or advanced physical-chemical processes either of the black water effluent or this effluent combined with grey water. The *recovery* percentages of COD, N and P from black water along the chain are respectively 60% (as methane), 1% (as MAP) and 25 % (as MAP). If the generated sludge is reused the nitrogen and phosphorus recovery can be enhanced to respectively 6% and 75%. Sludge reuse as soil conditioner, however, will probably not be authorized due to the risk of spreading harmful micro-pollutants. Most nitrogen from the black water is lost to the atmosphere as N_2 gas during the OLAND process.

The advantages of the black-water treatment chain described above are most significant if high requirements are set to the prevention of emission of potentially harmful micro-contaminants from black water to the environment. The technology keeps most of these substances in a concentrated stream whose advanced treatment costs would be relatively low. With respect to recovery of biogas and nutrients it would have more advantages in temperate zones than in humid tropical climates like Vietnam, especially where agricultural reuse of effluent would be possible. In the tropics biogas recovery through anaerobic pre-treatment does not require heating of the wastewater, so that there is less need to drastically restrict the toilet flush volume and apply low-flush vacuum toilets. Rather complete recycling and reuse of valuable components from sewage (mixed black and grey water) is possible by means of a UASB reactor and post-treatment technology combined with effluent reuse in agriculture. Any reduction of the wastewater flow and a higher strength of the wastewater would, however, be favourable to this system as well, but the source-separation of black and grey water could be avoided. Of course, the conditions for agricultural reuse of effluent are not always available and other solutions for nutrient recovery and reuse will have to be found.

[101] Based on black water COD load of 57 g/cap.d.
[102] Recovery as methane gas.

6.5.7 Treatment of grey water and mixed grey water and stormwater

Grey water is obtained as an independent stream in systems where black water or urine and faeces are collected separately. This is the case in the on-site system groups 1 and 2 and the off-site groups 8 until 12 (chapter 5). According to the data given in chapter 5 (table 5.2) grey water, collected separately from black water, constitutes a flow in the order of 90 l/cap.d and typically conveys about 50% of the domestic wastewater load of COD, 7% of N and 25% of P. These figures are based on European circumstances. In developing countries significant deviations could exist, e.g. with regard to flows of phosphates from household detergents. Grey water may contain faecal contamination. The COD concentration of untreated grey water is comparable with medium-strength sewage (400 - 500 mg/l (Metcalf and Eddy Inc, 2003, p 186); 600 – 700 mg/l (Elmitwalli and Otterpohl, 2007). The N and P concentrations are considerably lower than in sewage, but generally sufficient for unhindered biological treatment (Zeeman et al., 2008).

For household on-site treatment and disposal of grey water soakage pits are often used.
If the effluent has to be reused, for example in toilet flushing, higher quality requirements are set and horizontal and vertical-flow reed bed filters and rotating biological contactors could be applied (Nolde, 1999). Other methods would be green walls and tower gardens (Zurbruegg and Tilley, 2007).

In off-site treatment systems grey water possibly combined with stormwater can be treated by all biological technologies also applied for sewage. Grey water conveys significantly less inert suspended solids than sewage if it is collected separately and is not mixed with stormwater. In that case, the influent could be delivered directly to the biological treatment stage omitting the preliminary and primary treatment (e.g. Imhoff tanks).

Three grey water treatment technologies

In this subsection three grey water treatment systems are presented (table 6.5.9).
In tropical climates (lowest water temperature $\geq$ 20 ^oC) grey water could be treated by means of an anaerobic pre-treatment (anaerobic ponds or UASB reactors) plus aerobic post-treatment process. The anaerobic pre-treatment stages, however, could be omitted at influent COD concentrations of less than about 300 mg COD/l, as their COD removal efficiency would be very low at such concentrations (6.5.3.3). In temperate climates a mechanized aerobic method would be preferable. The excess sludge in each of these proposed grey water treatment methods is well stabilized and can be treated by means of simple drying beds.

Table 6.5.9 Indicative values of parameters and performances in the treatment of grey water in pond system, UASB + aerobic attached growth system and extended aeration system (Q = 2,000 m^3/d, $COD_{tot, inf}$ = 580 mg/l).

	Unit	AP + FP	UASB + SAF	Extended aeration AS
References		[103]	[104]	[105]
Temperature	^oC	25	25	25
HRT_{tot} (waterline)	D	7.2	0.47	1.83
Energy consumption	MJe/cap.yr	0	n.a.	34 – 60 [106]
Energy production	MJpe/cap.yr	0	96[107]	0
Area required	m^2/cap	0.39 – 0.57	0.065 – 0.10	0.16 – 0.22
Removal efficiencies				
BOD_5	%	85 – 95	90 - 95	90 – 95
FC	%	95 – 99	95 - 99	95 – 99
Conditions in zones of most appropriate application		Warm climate; availability of flat land; low availability of maintenance	Warm climate; concentrated influent; high influent COD; demand for biogas; adequate maintenance warranted	Frequent and skilled maintenance warranted

The system of anaerobic (AP) and facultative ponds (FP) with an HRT of 7 days could be applied under tropical conditions where sufficient land is available, maintenance input is limited and the effluent is discharged to surface water or used for irrigation. The required surface area for an AP + FP plant serving 20,000 inhabitants would be about 10,000 m^2. The required surface area is about five times larger than the UASB + Submerged Aerated Filter option.

The system consisting of UASB pre-treatment and post-treatment by means of a submerged aerated biofilter (SAF) would work best under (sub-) tropical conditions where frequent skilled maintenance can be warranted. The treatment of grey water by means of an UASB reactor (lab scale) at 30^{o}C with hydraulic retention times ranging from 6 to 16 hr showed

[103] (Arthur, 1983; Reed et al., 1995, p 119; Von Sperling and De Lemos Chernicharo, 2005, p 611).

[104] (Gonçalves et al., 1998; Canziani et al., 1999; Von Sperling and De Lemos Chernicharo, 2005, chapters 27.2 and 45). The energy production from grey water in a UASB reactor was calculated on the basis of data from Elmitwalli and Otterpohl (2007).

[105] (Metcalf and Eddy Inc, 2003, p 682, figure 8-7(a), p 747). The assumed F/M ratio is 0.06 kg BOD_5/kg MLSS.d.

[106] The energy consumption for extended aeration treatment of sewage (72-126 MJe/cap.yr) (Von Sperling and De Lemos Chernicharo, 2005, p 851) has been proportionally adapted to the lower COD load of grey water (52 g/cap.d instead of 109 g/cap.d).

[107] Grey water COD load = 52 g COD/cap.d; removed COD_{tot} = 52%; captured as methane 77% of removed COD_{tot}. Methane captured = 21 g CH_4-COD/cap.d (5.2 g CH_4/cap.d) (based on experiments at 30^o C by Elmitwalli and Otterpohl (2007).

COD_{tot}, N_{tot} and P_{tot} removal efficiencies of respectively 52 - 64, 22 – 30 and 15 – 21%. The percentages of influent COD_{tot} converted to methane amounted to 51, 40 and 38% at repectively 16, 10 and 6 hrs hydraulic retention time (Elmitwalli et al 2007).
Assuming a digestion efficiency of 40% and a methane recovery factor of 0.67 (Van Haandel and Lettinga, 1994) the heat value of produced methane is estimated at approximately 47 MJpe/cap.yr[108]. At a generator efficiency of 33% the corresponding output of electrical power would be about 15 MJe/cap.yr. As the energy consumption of the post-treatment submerged aerated biofilter (SAF) is presumably higher than the production from biogas, the UASB-SAF system for grey water would not be self-sufficient in terms of electrical power.
The footprint of 1,500 m^2 for 20,000 inhabitants is relatively small. UASB pre-treatment is not feasible where the influent COD concentration is lower than about 300 mg/l.

The extended-aeration activated sludge system could work in a wide range of temperatures, although at high temperatures nitrogen gas bubbles formed through de-nitrification could lead to settling problems in the clarifier[109]. The system requires an electric energy input of 34 – 60 MJe/cap.d and the land requirement of about 4,000 m^2 for a 20,000 inhabitants plant.

Fate of nutrients
The total nitrogen and phosphorus discharged in grey water (without kitchen refuse) amounts to 0.36 kg N/cap.yr and 0.18 kg P/cap.yr, which is approximately 7% of the domestic load of N and 25% of the domestic load of P respectively. The removal of nutrients during grey water treatment takes place through separation of particles and uptake in biological sludge. Some nitrogen removal through nitrification - denitrification could take place in ponds and aerobic attached growth systems. The fraction of the total discharged N and P recovered in reusable sludge will anyhow be small. If e.g. 30% of P would be removed through uptake in sludge in an UASB + submerged aerated filter system (table 6.5.5), this would amount to 0.054 kg P/cap.yr or 7% of the total load of P in domestic wastewater. As hardly any studies have been done on the N and P removal during grey water treatment, no attempt is made here to further detail the nutrient performance of the various treatment systems.

The effluent of grey water treatment in extended aeration and UASB + SAF plants could be reused for toilet flushing, though depending on the attained quality additional disinfection could be necessary.

Though practical experience may eventually show different results, it can be expected that in the temperate climate zones a sanitation system treating separate concentrated black and grey water can at least be self-sufficient in terms of energy, which is a clear advantage over the present mechanized aerobic treatment systems. If UASB sludge can not, for legal reasons or lack of stakeholder acceptance, used in agriculture, the P recovery is limited to the formed struvite alone and can be considered disappointing (25% of the P in black and grey water). In the tropics efficient energy recovery from sewage can be attained by means of UASB reactors without the need of separation of concentrated black water and grey water.

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[108] Influent COD is 52 g/cap.d. The calculated CH_4 production is 2.56 g/cap.d. The corresponding heat value 2.56 * 365 * 50.4/1000 = 47 MJpe/cap.yr.
[109] Prof Dr A.C.van Haandel, personal communication.

6.5.8 Treatment and utilization of urine

Separate treatment and utilization of urine is an element in the system groups 2, 5, 7, 8, 10 and 12 (chapter 5). Urine contains about 10% of the COD, 80% of the nitrogen, 50% of the phosphorus and 60% of the potassium produced in the household and its volume is about 1.25 l/cap.d (Chapter 5 tables 5.1 and 5.2). Annually one person excretes with urine approximately 4 kg of nitrogen (N), 0.36 kg of P, and 1.3 kg of K. Agricultural tests have shown that diluted urine is an effective fertilizer (Peter-Froehlich et al., 2007), a fact that is also known from long experience in Vietnam. Accordingly human urine can be considered a relevant source of fertilizing substances. However, pathogenic organisms, mostly from faecal origin (Höglund, 2001), residues of pharmaceutical products and salts constitute risks associated with the direct utilization of urine as a fertilizer. The heavy metal content of urine is very low.
The separate collection of urine is practiced all over the world and is achieved by means of urine-diverting dry (Höglund, 2001; Winblad and Simpson-Hébert, 2004) and flush toilets (e.g. Sweden (Höglund, 2001), Germany (Peter-Froehlich et al., 2007), Switzerland (Novaquatis-project)). According to findings of the Swiss Novaquatis project urine-diverting flush toilets collect not more than 60 – 75% of the excreted urine as a separate source stream[110]. Here, storage, transport, treatment and utilization of urine are briefly discussed.

Storage

Storage of urine is an element in all systems in which the collected urine is not continuously treated and used. A distinction is made between short-term storage where urine is immediately used for fertilization of the users' garden (a practice in Vietnam) and long-term storage where it serves as a fertilizer for general crop production. During storage the urea present in urine is rapidly hydrolysed to ammonium/ammonia and (bi-)carbonate, which leads to a pH rise and the formation of carbonates and phosphate precipitates (Maurer et al., 2006). In addition, pathogenic organisms die-off, so that in general the health risks are considered acceptable after storage of urine during 6 months at 20^o C (Höglund, 2001, p. 51). High temperatures and an increased pH value of about 9 promote the die-off of pathogenic organisms.

Collection and transport

Collection and transport takes place by cartage or by pipes or by a combination of the two. In the off-site options of groups 5, 7, 8, 10 and 12 the urine is collected by pipe from the urine-diverting toilets and led to urine tanks under or near the house. These tanks are emptied regularly and the urine transported by truck to fields or a urine-processing plant. According to the transport model introduced in subsection 6.4.10 (table 6.4.2) a urine recovery of 70% would yield 0.32 ton of urine/cap.yr and a primary energy requirement for transport of 14.1 MJpe/cap.yr under the assumption that the transporting truck has to travel 10 km for each load.

Treatment and utilization

Three methods of urine treatment and utilization are briefly discussed here. The first, most simple, way is direct application to land. According to the author's observations this practice is exercised where urine-diverting dry toilets are used, e.g. in the North of Vietnam. Irrigated crops come in direct contact with possible contaminations of the urine, like residues from

[110] www.novaquatis.eawag.ch/arbeitspakete/nova3/index_EN (last accessed on 29-07-08).

pharmaceuticals. Although not much is known yet about the risks, this is, at least hypothetically, a disadvantage of this method.

The second way is co-composting. Nghien and Calvert (2000) reported about a Vietnamese rural area where urine from dry urine-diverting toilets was added to compost heaps, diluted and used successfully on mango trees, and mixed with animal urine and manure and subsequently used to grow flowers. Application of source-separated urine to enrich compost could be carried out on urban scale as well.

The valuable nutrients in urine can be extracted also by means of technological processes. The products of extraction are easy to handle and much less contaminated by harmful impurities, which is an important advantage of this approach. In particular the recovery of phosphorus from urine meets growing interest as this element is due to become scarce (Driver et al., 1999; Cordell et al., 2009). One way to accomplish P-recovery is through magnesiumammonium-phosphate (struvite) precipitation, a process described above. For removal of most potentially harmful micro-pollutants from urine ozonation seems to be the best technology at the moment (Maurer et al., 2006).

Wilsenach (2006, chapter 3) has pointed out the advantage of separate collection and treatment of urine in terms of energy savings at central wastewater-treatment plants with biological nitrogen and phosphorus removal. As the treatment plant receives sewage with less nitrogen, less aeration energy is needed for nitrification. Such urine diversion could be realized by means of urine-diverting flush toilets and urinals as suggested in system groups 5 an 7 (Chapter 5). Wilsenach has compared the energy consumption in (1) a regular aerobic treatment plant and (2) a plant with separate treatment of source-collected urine. In both options excess sludge is digested in an anaerobic digester. The produced biogas is used for the plant's own energy supply, and struvite precipitation and SHARON/Annamox process are applied to remove phosphorus and nitrogen from the supernatant of the anaerobic digester.
In regular biological wastewater- treatment plants used in The Netherlands phosphate is removed biologically by means of phosphate accumulating sludge, and nitrogen through nitrification and de-nitrification, processes that require relatively large bioreactor volumes and much energy for aeration. The average continuous power requirement of this system is estimated at 11.5 Wpe/cap (~363 MJpe/cap.yr) (Wilsenach, 2006, p 118). Source-separation of urine strongly reduces the nitrogen and phosphorus load in the incoming sewage, so that the volume of the aeration tanks can be much smaller, less aeration energy is needed and less organic matter is required for de-nitrification, which can be fed to the anaerobic sludge digester for the production of methane gas. Accordingly, the power requirement of the wastewater- treatment process in which 50% of the urine is collected separately and treated jointly with anaerobic digester supernatant is reduced from 11.5 to 2.5 Wpe/cap (~79 MJpe/cap.yr). The estimated net energy consumption (total consumption minus production at the plant) in both options is summarized in table 6.5.10.

Table 6.5.10 Energy consumption at municipal wastewater-treatment plants with and without separate urine collection and treatment. In both scenarios N and P are treated by means of a combined struvite precipitation and SHARON/Annamox process (based on Wilsenach(2006)).

System	Net primary energy consumption for sewage treatment (MJpe/cap.yr)
Municipal wastewater treatment with biological N and P removal and anaerobic digestion of excess sludge	363
Municipal wastewater treatment with separate urine treatment and anaerobic digestion of excess sludge (50% of urine separate at source)	79

In summary, the strengths of urine diversion as proposed in the options of system groups 2, 5, 7, 8, 10 and 12 (Chapter 5) lie in convenient handling of faecal matter in dry dehydrating toilets (6.2.1), relatively simple recovery of nutrients, cost-effective reduction of nitrogen and phosphorus emissions and saving of expenses (among which is energy) at central wastewater-treatment plants. Drawbacks are the more complicated urine-diverting toilets and the operation of a separate urine handling system.

6.5.9 Off-site treatment of faecal and treatment sludges

The twelve on-site and off-site drainage and sanitation system groups proposed in chapter 5 generate various types of sludge as presented in table 6.5.11. In this subsection the treatment of these sludges is briefly discussed.

Table 6.5.11 Overview of sludge types and reference to group classification.

Sludge types[111]	Sanitation system group
Faecal sludge	1, 3, 4, 5, 6, 7
Faecal matter from dehydrating toilets	2, 8, 10
Sludge from black water treatment	9, 11
Sludge from sewage and grey water treatment	4 – 12

These sludges consist of degradable organic matter and inert material and may contain valuable components, particularly nutrients, but often also hazardous components, notably heavy metals, pathogenic organisms and pharmaceutical residues. Accordingly, the challenge is to find a chain of treatment and disposal or utilization of sludges that maximize the benefits and minimize negative health and environmental impacts.

A full treatise of sludge management methods for wastewater-treatment plants can be found in Metcalf and Eddy Inc (2003). Rulkens (2008) reviews the options of energy generation from sewage sludges and Strauss et al. (1997) the options for *faecal sludges* from on-site sanitation.

In situations where there are medium or large-scale off-site sewage treatment plants the faecal sludges from on-site treatment (septic tanks) are often added to the influent stream or to the sludge treatment line. The faecal matter from dehydrating toilets can be utilized directly on-site or co-composted (Strauss et al., 1997; Cofie et al., 2006; Koné et al., 2007).

[111] For definitions of the sludge types: see glossary.

Here, the discussion of sludge-treatment is limited to (1) anaerobic digestion of highly biodegradable sludge (6.5.9.1) and (2) dewatering by means of thickeners, ponds, sand beds and planted filters (6.5.9.2). Special attention is paid to pathogen removal. These technologies can be applied to faecal sludge and septic tank sludge from on-site treatment and waste sludge from municipal wastewater-treatment plants.

6.5.9.1 Anaerobic digestion of biodegradable sludge

Biological wastewater-treatment processes, in particular the high-rate mechanized technologies, generate substantial quantities of biodegradable primary and secondary sludge. For high-rate aerobic technologies this is in the order of 0.45 kg TSS/kg COD received at the wastewater-treatment plant ((Metcalf and Eddy Inc, 2003, p 1436).

By means of anaerobic digestion the sludge can be stabilized and a part of the energy content of the sludge can be recovered and applied to generate electricity and heat by means of a combined heat and power (CHP) unit (see also subsection 6.3.3.2). Accordingly, digesters are widely used in combination with aerobic wastewater-treatment technologies. The required retention time of the sludge in anaerobic digesters depends on the temperature and the application of mixing. In mixed digesters of the CSTR type the required retention times at 25 and 35^{o} C are 20 and 10 days respectively (Metcalf and Eddy Inc, 2003, p 1511). In unmixed digesters the assumed retention times are longer. With sludge digesters a volatile solids (VS) conversion of 40 – 55% is achieved (Von Sperling and De Lemos Chernicharo, 2005, p 1222). During the digestion part of the phosphorus and nitrogen stored in the sludge solids is released to the supernatant. Under mesophilic conditions the degree of hygienization of sludge is small. Riau and co-authors (2010) found a removal of faecal coliforms (FC) of (only) 26 % after a retention of 15 days in lab-scale reactors at a temperature of 35 ^{o}C. Under the same conditions the reduction of the Salmonella spp. count was about 90%. The achieved reductions were insufficient to produce a digested sludge that complied with the US biosolids class A pathogen indicator density limits of less than 10^{3} FC/g TS, less than 3 Salmonella spp/4 g TS and less than 1 viable HE/ 4 g TS (National Research Council, 1996, p. 123).

A combination of a first stage of thermophilic and a second stage of mesophilic digestion can lead to better results in terms of reduced digestion time, volatile solids (VS) mineralization, methane production and sludge hygienization than mesophilic digestion alone. In a batch experiment treating combined primary and secondary sludge during 6 days under thermophilic followed by 15 days under mesophilic conditions a volatile solids removal of over 50% and a faecal coliform reduction of more than 99% were obtained, so that the product sludge amply fulfilled the requirements of class A biosolids. This product could be safely utilized as soil conditioner (Riau et al., 2010). The removal of helminth eggs (HE) in thermophilic digesters is better than in mesophilic digesters as well. For the total HE count removal efficiencies of 35 and 70% were measured in a mesophilic and thermophilic digester respectively. The more advanced elimination by thermophilic digesters was more pronounced even for the viable helminth eggs (HE_{larval}) (Rojas Oropeza et al., 2001). Nevertheless, depending on the viable helminth count of the raw influent sludge, thermophilic digestion will not always be a sufficient treatment technology to deliver a viable helminth count in the final sludge that complies with the requirements of class A biosolids.

According to Coenen and co-authors (Coenen et al., 2005) anaerobic sludge treatment of combined primary and secondary sludges in Dutch wastewater-treatment plants provides an energy output of about 29 MJe/cap.yr at a total demand of an aerobic activated sludge treatment plant of 94 MJe/cap.yr. Consequently, anaerobic digestion supplies on average about 30% of the electricity demand at the Dutch sewage treatment plants with anaerobic sludge digestion.

The produced stabilized digestate can be more easily dewatered than raw sludge, either by mechanical means or on sludge drying beds (subsection 6.5.9.2). Sludge from primary and secondary sedimentation tanks usually passes through thickeners before being fed to anaerobic digesters in order to reduce the sludge flow and accordingly the volume of the digester(s). Thickeners are designed on the basis of a sludge loading rate of 100 kg TSS/m^2.d for primary sludge, 30 kg TSS/m^2.d for secondary sludge from activated sludge plants and for mixed primary and secondary sludges (Metcalf and Eddy Inc, 2003, p 1492).

Anaerobic digestion can also be applied to sludge from septic tanks (septage) where this sludge is not sufficiently stabilized to be spread onto drying beds for dewatering (Valencia et al., 2009).

6.5.9.2 Dewatering of stabilized sludge

Two low-tech methods for sludge dewatering are briefly described: conventional sand-based drying beds and planted sludge drying beds. Since these methods are rather land-intensive, they are deemed less suitable for communities of more than 20,000 inhabitants (Metcalf and Eddy, 2003 p 1570). They can be used for the treatment of partly stabilized faecal sludge from septic tanks and Imhoff tanks. Methods more suited for large scale centralized treatment plants can be found in literature (Metcalf and Eddy Inc, 2003, chapter 14).
The flow per capita and quality of faecal sludges are highly variable depending on their origin and the de-sludging technique applied. For septic tank sludge most of the reported mass flow values vary between 0.5 and 1 l/cap.d and a dry matter (TS) content in the range of 5 to 20 g/l (Accra: 7 g/l (Strauss et al., 1997), Bangkok: 15 g/l (Koottatep et al., 2005). BOD_5 values may vary from about 0.1 to about 80 g/l with common values in the order 5 g/l (Argentina: 7 g/l (Ingallinella et al., 1996), Bangkok: 2.3 g/l (Koottatep et al., 2005).

Preliminary dewatering by means of thickeners and ponds

The first step in dewatering can be a sludge thickener (subsection 6.5.9.1) or a pond in which the sludge settles and the bulk of the water can be separated. Sludge settling ponds may have a hydraulic retention time of about 10 days and a solids retention time of several months. The subsequent dewatering of the thickened sludge takes place through percolation of leachate into a drying bed and evaporation. Since percolation is most important, the drying bed needs to be provided with a drainage system. The decanted liquid is treated as wastewater; the dried sludges are discharged as solid waste or utilized as soil conditioner, depending on their quality. Two techniques of sludge drying are introduced here: sand-based drying beds and planted drying beds.

Sand-based drying beds

Sludge drying beds consist of package of sand and gravel with a depth of 15 to 25 cm onto which intermittently the (partly) stabilized sludge is deposited with a batch sludge depth of less than 30 cm. The design loading rate is in the order of 100 - 200 kg TS/m^2.yr. The drying time is in the range of 10 to 15 days under favourable conditions (Metcalf and Eddy Inc, 2003, p 1572; Cofie et al., 2006). Conventional drying beds for mechanized wastewater treatment plants cover 30 – 40% of the surface of the total wastewater-treatment plant. During the drying process further die-off of pathogens that might have survived previous treatment steps takes place. The final product of drying beds usually has a TS content of about 40% and can be used as a soil conditioner unless its quality is deficient. The better dried and stabilized the deposited sludges are, the less problems with malodours and insects may be expected. At drying of faecal sludge from the city of Kumasi (Ghana) from a TS content of 2 to 3% to a final content of 20% the initial Ascaris and Trichuris eggs count of 60 eggs/g TS was reduced by about 50% (Koné et al., 2007). This was certainly insufficient for safe reuse of the dried product. This count was further reduced to a safe level by composting. In climates with a long wet and dry season like Vietnam, wet sludge can be stored in ponds during the wet season and spread on the drying beds during the dry season.

Planted drying beds
Instead of the conventional sand-gravel drying beds planted drying beds may be used (also named constructed wetlands). The planted drying bed consists of a sand-gravel bed with a depth of 65 cm planted with reed, cattails or other helophytes and provided with drains for percolate collection. In comparison with conventional drying beds, the presence of plants enables higher admissible loading rates of about 250 kg TS/m^2.yr (under tropical conditions), higher allowable accumulation of sludge on the bed (up to 80 cm with an annual accumulation of 12 cm) and consequently leads to a lower footprint and a low bed cleaning frequency. By virtue of long sludge retention times a high pathogen removal percentage can be achieved, so that the produced biosolids are suitable as soil conditioner (Koottatep et al., 2005; Kengne et al., 2009). An example of a planted drying bed for septage treatment in Vietnam can be found in the city of Nam Dinh (Klingel et al., 2001; Koottatep et al., 2005)[112]. There is no mention in literature yet of the application of planted drying beds for the treatment of sludge from (small) sewage treatment plants.

6.5.10 Energy consumption in wastewater treatment

Energy in wastewater treatment is used for pumping, aeration, mixing, sludge scrapers, heating of digesters, sludge dewatering and sludge transport. Also energy can be incorporated in chemicals applied for treatment, such as the methanol used for post-de-nitrification (Wilsenach, 2006, p 118). The bulk of the energy consumed in mechanized aerobic wastewater treatment is for aeration. In the performance matrices of wastewater-treatment technologies energy consumption data were presented for as much as these data were available in or could be derived from literature. The per capita energy consumption depends on the following factors:

- Nature of the treatment technology;
- Climate;
- Plant capacity;
- Per capita hydraulic load;
- Per capita load of pollutants;
- Effluent requirements.

112 http://www.eawag.ch/organisation/abteilungen/sandec/publikationen/publications_ewm/downloads_ewm/WSA_paper_Klingel.pdf (last accessed: Aug 11, 2010).

Energy consumption in the first place depends on the nature of the treatment technology: non-mechanized treatment methods may have a consumption close to zero, while mechanized aerobic methods have a relatively high per capita consumption. Also climate plays a role. In warm climates for example sewage can be treated by anaerobic technologies which yield biogas as a source of energy, while in cold climates energy is needed for heating of digesters. Energy consumption further depends on plant capacity. At capacities smaller than 150,000 m^3/d the energy consumption increases with decreasing capacity (Metcalf and Eddy Inc, 2003, p 1705). On the other hand energy may be gained through anaerobic sludge digestion and incineration of excess sludge. The per capita energy consumption of mechanized aerobic systems increases with increasing per capita hydraulic and pollutant loads and required COD and ammonia treatment efficiencies. Net energy consumption (gross consumption minus production) may decrease through measures that increase the utilization of methane generated from the organic matter in wastewater and the energy obtained in the incineration of excess sludge, and measures that decrease the hydraulic and COD and NH_4^+ loads to aerobic treatment processes. Sanitation systems that minimize the need of energy and maximize the energy recovery via biogas generation can have a positive energy yield, especially in tropical countries.

Table 6.5.12 reviews values of the energy consumption and generation in various wastewater-treatment technologies under various conditions. From the table can be concluded that the energy consumption of activated sludge plants without anaerobic sludge digestion varies between 216 and 378 MJpe/cap.yr. The differences can in part be explained by different capacities and loading rates. Through utilization of biogas from anaerobic digestion of excess sludge the energy consumption at activated-sludge plants can be reduced by about 90 MJpe/cap.yr (derived from Coenen et al. (2005)). Trickling filters and UASB + activated sludge treatment plants have a consumption in the order of 175 MJpe/cap.yr, which is lower than the consumption at activated sludge plants. Through separate collection and treatment of urine the energy consumption can be reduced to under 100 MJpe/cap.yr (derived from Wilsenach (2006)). A net energy yield could occur at plants that treat sewage by means of UASB reactors plus ponds (in the (sub)tropics), and at decentralized treatment plants in a temperate climate with separate treatment of concentrated black water and grey water where the organic matter from both streams is treated by means of a UASB reactor and the generated biogas is utilized.
It can be concluded, that the net consumption of energy for primary plus secondary wastewater treatment by means of activated sludge plants with anaerobic sludge digestion or by means of trickling filters is in the same range as the collection of sewage by means of gravity sewer systems in flat areas (213 MJ_{pe}/cap.yr) (table 6.4.3). Although energy consumption/generation certainly is interesting with regard to reduction of greenhouse gas emissions, it should be noted that its importance in terms of operational costs or benefits of a sanitation system is of little significance. A total per capita energy demand of a sanitation system (sewage collection and treatment) of 500 MJpe/cap.yr is more or less equal to the energy consumption of a lamp of 5 – 6 Watt permanently switched on.

Table 6.5.12 Net energy consumption of wastewater-treatment plants.

Climate	Wastewater	Treatment method	Energy consumption (MJpe/cap.yr)	Reference
Temperate	Mun. Sewage, 15,250 m^3/d	Activated sludge, AD, N and P removal	363	(Wilsenach, 2006, p 120)
Temperate	Mun. sewage – 50% urine, 15,250 m^3/d	Activated sludge, AD, N and P removal	79	(Wilsenach, 2006, p 120)
Temperate	Mun. Sewage, Average Nether-lands	Activated sludge, N and P removal Without AD	282	(Coenen et al., 2005)
Temperate	Mun. Sewage, Average Nether-lands	Activated sludge, N and P removal with AD	194	(Coenen et al., 2005)
Not indicated	Mun. Sewage, 50,000 m^3/d	Activated sludge, Nitrification and filtration	372[113]	(Metcalf and Eddy Inc, 2003, p 1705)
Not indicated	Mun. Sewage, 50,000 m^3/d	Activated sludge	263	(Metcalf and Eddy Inc, 2003, p 1705)
Not indicated	Mun. Sewage, 50,000 m^3/d	Trickling filter	175	(Metcalf and Eddy Inc, 2003, p 1705)
Warm	Mun. Sewage, capacity not indicated	Extended Aeration	216 – 378	(Von Sperling and De Lemos Chernicharo, 2005, p 851)
Warm	Mun. Sewage, capacity not indicated	UASB + activated sludge	151 – 216[114]	(Von Sperling and De Lemos Chernicharo, 2005, p 851)
Warm	Mun. sewage, 40,000 m^3/d[115]	UASB + ponds	- 153	(Van Haandel and G. Lettinga, 1994)
Temperate	Conc. black water (34 m^3/d) and grey water (414 m^3/d)	Separate black and grey water treatment[116]	Production instead of consumption	(Wiegant, 2007)

113 According to Metcalf and Eddy (2003) the electrical energy consumption of a plant with a capacity of 50,000 m^3/d equals 1700 MJe/1000 m^3. Assuming a per capita sewage generation rate of 0.2 m^3/cap.d and an electricity generation efficiency of 33%, the primary energy consumption is 1700/(1000/0.2) * 3 * 365 = 372 MJpe/cap.yr.

114 The range given by Von Sperling and Chernicharo (2005, p 851) does not take into account the energy recoverable from biogas. The recoverable energy from biogas generated at the UASB reactor fed with sewage is about 150 MJpe/cap.yr (Van Haandel and G. Lettinga, 1994, p 120), so that the net energy consumption of UASB + activated sludge plants can be between 0 and 60 MJpe/cap.yr.

115 The example given by Van Haandel and Lettinga (1994, p 120) refers to an UASB reactor serving 200,000 PE and converting 10,000 kg COD/d. With a flow of 0.2 m^3/d the capacity of the plant would be 40,000 m^3/d. The generated methane would be 1,670 kg/d with a heat value of 84,000 MJ/d. This is 84,000/200,000 * 365 = 153 MJpe/cap.yr. It is assumed that the post-treatment ponds do not require energy input.

116 The modeled black-water treatment system consists of a UASB reactor followed by $FePO_4$ precipitation, Brammox reactor and sand filtration. The grey water is treated by UASB reactor followed by a membrane bioreactor system.

6.5.11 Selection of treatment options for source-separated wastewater

In addition to the technologies for the treatment of sewage (subsections 6.5.2 – 6.5.5) in the above subsections 6.5.6 to 6.5.9 the treatment of source-separated black water, grey water, urine and excess sludges were introduced. The aim of the present subsection is to enable making the selection of feasible technologies for a situation under study. This is done by summarizing the performance data of the mentioned technologies in a screening matrix (table 6.5.13) and in a table showing their strengths and weaknesses and conditions of most appropriate application (table 6.5.14). The chosen restrictive factors in the screening matrix are partly the same as those used for sewage treatment technologies (table 6.5.6): temperature, lack of availability of skilled surveillance, power and spare parts, unavailability of regular maintenance, limited availability of flat land and. In addition the factors lack of practical local demand for biogas and nutrients from wastewater has been added. The meaning of the restrictive factors to the treatment of the different types of wastewater is briefly discussed.

Concentrated Black water

For concentrated black water, collected by means of vacuum systems, and treated by ASTR or the UASB-septic tanks – struvite – OLAND treatment system the relevant restrictive factors are: lack of operational skills and maintenance frequency. A temperature < 20^{o} C does not have to be a constraint as the treatment technologies for vacuum collected black water usually include heating of the anaerobic and OLAND reactors making use of the biogas generated by the system. A strength of these separate black water treatment systems is the possibility of recovery of biogas and phosphate (in sludge and struvite). With additional post- treatment measures emissions of pathogens and organic micro-pollutants, like pharmaceuticals, to the environment could probably be controlled more easily in these systems than in regular sewage treatment plants, as the flow per capita is much lower. If there is no practical demand for recovered biogas and phosphate and no need to control emissions of micro-pollutants the application of the system of separated black and grey water treatment would be doubtful.

Grey water

As grey water resembles sewage, the same secondary treatment technologies with the same restrictive factors could be applied. Here, only 1 non-mechanized and 2 mechanized treatment technologies are listed. Pond systems for grey water are unfeasible at low temperatures (< 20^{o} C) and where sufficient flat land is unavailable. UASB plus submerged aerobic filter treatment is limited by low temperatures and lack of skilled and regular basic maintenance. The extended aeration technology needs skilled and regular maintenance as well and is unfeasible at the absence of these.

Urine

Urine treatment consists of storage and urine utilization. Storage is supposed to be feasible under all practical conditions. Direct application to land is unfeasible where a practical local demand for nutrients is absent. Urine can be co-composted with for example market wastes and may serve to increase the nutrient content. Co-composting is not implementable where minimum maintenance requirements are not satisfied. Recovery of phosphorus (struvite reactor) and removal of nitrogen are not feasible where the rather complicated operational care is not warranted. As the application of struvite is not dependent on *local* demand, it may be assumed that lack of local demand for struvite is not a restrictive factor to the Struvite-SHARON/ Annamox treatment chain.

Sludges

Anaerobic digestion of excess sludges from septic tanks and off-site wastewater-treatment plants can be executed by means of simple and technically more advanced technologies.

The relevant restrictive factor is regular maintenance without which the process would fail.

Anaerobic sludge treatment yields biogas, but could even be a feasible, though less desirable, option for sludge stabilization where this gas cannot be reused. In temperate climates the produced gas is used for heating the digester to the mesophilic temperature range.

Simple sludge drying beds and planted filters are feasible in any situation where sufficient land is available. As mentioned the land need for drying beds can be rather high in the order of 0.10 m^2/capita.The table 6.5.13 makes clear that in situations of land scarcity other (mechanized) sludge-dewatering methods have to be selected.

Table 6.5.13 Screening matrix concerning treatment options for source-separated wastewaters and sludges.
(+ feasible; +/- feasibility is doubtful; - non-feasible; X = factor irrelevant to technology)

Technologies / Restrictive factors	Concentrated black water (vacuum collected)		Grey water			Urine			Treatment sludges	Stabilized sludges	
	Anaerobic digestion (ASTR)	UASB + struvite + OLAND	AP + FP	UASB + SAF	Extended aeration	Direct application on land	Co-compos-ting	Struvite precipitation + SHARON/ Annamox	Anaerobic digestion (ASTR)	Sludge drying beds	Planted filters
Temperature < 20° C	+	+	-	-	+	+	+	+	+	+	+
Frequent skilled surveillance, power and spare parts not guaranteed	+	-	+	-	-	+	+	-	+	+	+
Regular basic maintenance not guaranteed	-	-	+	-	-	+	-	-	-	+	+
Limited availability of flat land	+	+	-	+	+	+	+	+	+	-	-
No practical local demand for excess biogas	+/-	+/-	+	+	X	X	X	X	+	X	X
No practical local demand for nutrients from municipal wastewater	+/-	+	+	+	+	-	-	+[117]	+	+	+
Text reference	6.3.3	6.5.6	6.5.7	6.5.7	6.5.7	6.5.8	6.5.8	6.5.8	6.5.9	6.5.9	6.5.9

[117] Separate urine collection and treatment could be attractive as much energy is saved due to lower N and P loads to the aerobic treatment process (section 6.5.8). Therefore, this system option could be feasible even in the absence of local nutrient demand.

Table 6.5.14 Strengths, weaknesses and conditions of most appropriate application of treatment options for source-separate wastewater.

Wastewater	Concentrated black water from vacuum toilets		Grey water from households with source-separation of feaces and black/brown water			Urine from households with source separation of urine		
Treatment technologies	Anaerobic digestion (ASTR)	UASB + struvite + OLAND	AP + FP	UASB + SAF	Extended aeration	Storage and direct application on land	Co-compos-ting	Struvite prec^n and SHARON/ Annamox
Text reference	6.3.3	6.5.6	6.5.7	6.5.7	6.5.7	6.5.8	6.5.8	6.5.8
Strengths	Robust; biogas utilization	Biogas utilization, phosphate recovered in pure form	Robust; no energy consumption; very low maintenance requirement	High effluent quality; low energy consumption; small footprint	High effluent quality; suitable for any influent COD concentration	Simple; full benefit of available nutrients	Simple; pathogen elimination; no rest products	Phosphate recovered in pure form
Weaknesses	Wet slurry transport to land could be expensive; risk of micro-contaminants in treated slurry[118]	Complex; frequent and skilled maintenance required; nitrogen is lost; effluent needs post-treatment[119]	High land requirement; water loss through evaporation	Regular maintenance; requirement of high influent COD	Regular maintenance; high energy consumption	Contamina-tion of crops by pathogen and organic micro-contaminants	Contamina-tion of compost with organic micro-contaminants	Complex; frequent and skilled maintenance required; nitrogen is lost
Conditions in zones of most appropriate application	Need of energy and nutrients recovery; utilization of digestate directly or after dewatering	Need of energy and phosphate recovery; direct application of digestate to land not allowed	Warm climate; availability of flat land; low availability of maintenance	Warm climate; influent COD > 600 mg/l; demand for biogas; adequate maintenance warranted	Frequent and skilled maintenance warranted	Croplands close to source of urine; low requirements to prevention of crop contamination	Availability of composting plant; low requirements to prevention of crop contamination	High requirements to purity of products (recovered phosphate and effluent)

[118] with additional sludge treatment emissions of pharmaceuticals and other potentially harmful micro-pollutants can be prevented.
[119] with additional effluent treatment emissions of pharmaceuticals and other potentially harmful micro-pollutants can be prevented.

6.6 Recovery and utilization of valuable products from wastewater

Municipal drainage and sanitation chains generate waste streams that contain utilizable components, in particular water, organic matter and nutrients. While in the past these components were most often discharged into the environment, now their purposeful utilization is high on the agenda. The most important utilizable products from municipal wastewater are stormwater, effluents of wastewater-treatment plants, biogas, bio-solids and nutrients in several forms (table 5.4). Each form of utilization of a waste stream requires its specific product treatment dependent on the desired product quality. In this section the utilization possibilities of products from the main wastewater source streams are briefly discussed without, however, detailing the treatment technologies required to attain adequate product qualities.

Stormwater

Stormwater can be utilized for various purposes and at various scales. Well known purposes are: supply of drinking and other household water, artificial recharge of groundwater, irrigation, and recreational lakes. An utilization infrastructure can be laid out at the scale of households (Koenig, 2001), enterprises, communities and cities (Heaney et al., 2000). Storage can take place in surface reservoirs and in subterraneous aquifers. The latter solution reduces the evaporation loss of water. Utilization of stormwater not only reduces the amount of water to be supplied from other sources, but reduces the stormwater run-off and consequently the investments in drainage infrastructure.

Sewage and sewage sludge

Effluent from sewage-treatment plants can be reused for irrigation, for aquaculture, in industry and for aquifer recharge after adequate purification (chapter 5, system groups 4 and 6) (UNEP International Environmental Technology Centre and Murdoch University Environmental Technology Centre, 2002; Wang et al., 2008). *Energy* in the form of mechanical energy and heat can be obtained through the combustion of methane in biogas from anaerobic reactors and digesters used for the treatment of sewage (in warm climates), concentrated black and brown water, and primary and secondary sludge (Van Haandel and G. Lettinga, 1994; Rulkens and Bien, 2004; Kujawa-Roeleveld et al., 2006).

During biological sewage treatment the phosphate present distributes itself over the water and sludge phase. *Phosphate in water* is reused directly, if effluent is applied as irrigation water or for aquaculture. Phosphate can also be (partly) recovered from the effluent of sewage-treatment plants, from the decantate of anaerobic digestion and from a side-stream of the anaerobic first phase in biological nitrogen and phosphate removal. The recovery processes proposed most often are precipitation as calciumphosphate (Crystalactor® process) or struvite (Battistoni et al., 1998; Piekema and Giesen, 2001).

Phosphate (and nitrogen) concentrated in excess sludge of sewage-treatment plants is recovered in the following ways. If this treatment sludge can be used as soil conditioner without unacceptable agronomic, environmental and health risks, nutrients can be directly valorized. If sludge is considered too polluted for direct soil application, it has to be incinerated after which the phosphate can be recovered from the ashes of the incineration plant (Geraats et al., 2007). Direct reuse of effluent and sludge in agriculture may lead to a very effective utilization of nutrients and can be applied both at small and large scale. Special attention has to be given to risks related to the presence of pathogenic microorganisms, organic micro-pollutants and salts (including salts of heavy metals). There is also the risk of over-fertilization if undiluted wastewater-treatment effluent is used for irrigation on the same area over a long period of the year. Application of nutrient recovery technologies are especially suited to large wastewater treatment plants due to diseconomies of small-scale treatment. The storage of treated effluents prior to reuse can take place in deep surface reservoirs and the underground after infiltration. The latter storage method prevents evaporation losses.

Separate black and grey water

There hardly seem to be advantages for recovery of energy and nutrients in separate collection and treatment of domestic *grey water* and the *regular black water* from cistern- flush toilets. Though regular black water has the organic matter and nutrients in a more concentrated form than sewage, it is still too diluted to make the recovery of valuable energy and nutrients more efficient than in the case of sewage (Van Voorthuizen et al., 2008). The recovery processes of water, energy and nutrients can be run at a higher overall efficiency than recovery from sewage by using vacuum toilets that generate *concentrated black water* consisting of urine and faeces in a small volume of flush water (chapter 5, system groups 9 and 11) (Zeeman et al., 2008). The yield of the energy recovery could be increased by adding kitchen biowastes to the black-water stream (Kujawa-Roeleveld et al., 2006). *Grey water* constitutes a large fraction of the produced domestic wastewater and, depending on the type of detergents used, may contain a significant concentration of phosphate. After proper treatment grey water can play an important role in irrigation of crops (Morel and Diener, 2006, p 2). The recovery of energy from grey water by means of anaerobic treatment has a relatively low efficiency and is probably not feasible at a small scale(Elmitwalli and Otterpohl, 2007).

Separate urine, faecal matter/brown water and grey water

Separate collection of *urine* delivers a high fraction of the nutrients in domestic wastewater in a very concentrated form (chapter 5, system groups 2, 5, 7, 8, 10, 12). Urine, however, also contains a significant fraction of excreted pharmaceuticals and hormones, which may render it less acceptable for direct reuse. The nutrients in urine can be utilized either directly in the cultivation of vegetables, or recovered indirectly by chemical processes. In this thesis two technologies of at-source urine separation are discussed: the urine-diverting dry toilet and the urine-diverting flush toilet. In both toilet types the urine is collected in undiluted form. Much research attention is given to the recovery of phosphorus from urine in the form struvite (Maurer et al., 2006; Ronteltap et al., 2007).

There are several options for the utilization of components of *faecal matter* and *concentrated brown water* (faeces plus a little flush water) after separation of urine. If urine-diverting dry toilets are applied the moist *faecal matter* can be dehydrated during storage for elimination of pathogens and be used as soil conditioner (chapter 5, groups 2, 8 and 10) (Esrey et al., 1998, p 13). In the case of the application of urine-diverting flush toilets (groups 5, 7, 12) water, energy, and reusable sludge can be recovered from concentrated brown water using methods similar to the ones applied to concentrated black water. Where urine-diverting dry toilets are used, the generated grey water is usually infiltrated locally or used for watering plants (chapter 5, group 2).

Excreta and faecal sludges
Stored *excreta* from dry anaerobic toilets (chapter 5, system group 1) and *sludge from septic and Imhoff tanks* are not fully stabilized and contain faecal, possibly pathogenic, micro-organisms. This sludge can be used as soil conditioner after proper stabilization, disinfection and dewatering (for technologies see subsection 6.5.9).

6.7 Selection of drainage and sanitation systems

In the preceding sections strengths and weaknesses and the conditions of most appropriate application of several technologies including toilets, on-site storage and treatment, transport and off-site treatment are determined. Based on that analysis a decision tree for the choice between the different drainage and sanitation system groups introduced in chapter 5, table 5.3, is presented here. The decision tree facilitates the choice between feasible, or likely, and unfeasible, or unlikely, system options for a specific situation. The screening among the twelve system groups is carried out by means of the following factors which describe the physical and social conditions in which drainage and sanitation systems have to work.

- Hand-carried water or piped water in the house;
- Building density;
- Rainfall regime;
- Distance of stormwater transport;
- Set priority for resources saving, recovery and reuse;
- Possibilities of agricultural or aquacultural reuse of effluent.

The first two factors distinguish between on-site and off-site system groups; the second two between the use of combined and separate sewer systems, the fifth one between system groups with and without recovery of resources and the last factor between agricultural or aquacultural reuse of effluent and other ways to recover the resources from wastewater.
The impact of these factors on the system choice is analysed by means of questions that single out certain system groups as feasible and other as unfeasible in the situation under study. This has been elaborated to the decision trees presented in figure 6.7.1 and 6.7.2.

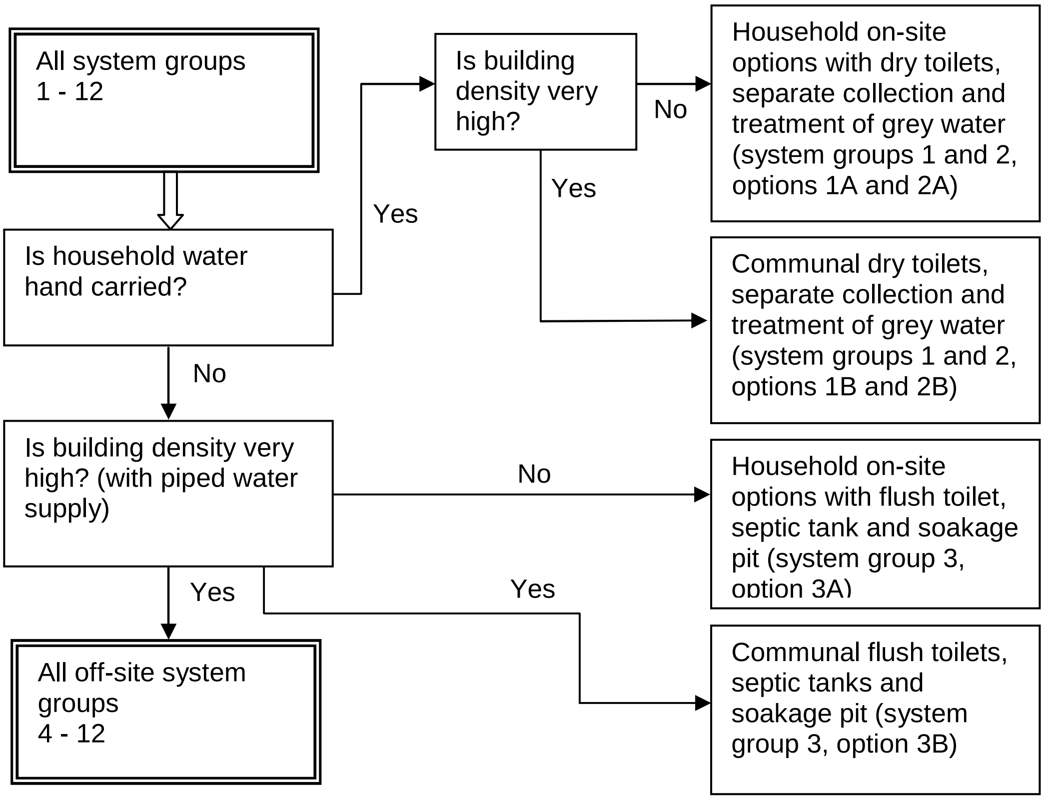

Figure 6.7.1 Decision tree for selection of on-site and off-site drainage and sanitation system groups.

The first question in figure 6.7.1 '*Is household water hand carried?*' distinguishes between useful application of dry on-site toilets and flush-based toilets. Here, it is assumed that where households use hand-carried water only dry toilet options are feasible and flush toilet options are unfeasible. Where piped water is used dry toilets could still be used, as is the case in the North of Vietnam where households in villages with piped water have dry urine-diverting toilets and grey water is discharged to rainwater channels[120]. If the choice for household on-site dry systems of system group 1 (anaerobic accumulating digestion toilets) and 2 (urine-diverting dry toilets) has been made, the next question about the '*building density*' distinguishes between household and communal dry toilets. At very high building densities as often occur in slum areas there are often no conditions for household on-site toilet options and communal toilets are the only feasible option. The question about '*building density*' in a situation with piped water supply distinguishes between household on-site treatment (group 3, option 3A) on the one hand and communal flush-toilet facilities (system group 3, option 3B) and off-site treatment (system groups 4 until 12) on the other. At high building density it is difficult to find space for on-site treatment at every household. In areas where households lack space for their own toilets communal flush toilet facilities may be provided. These may have their own septic tank and soakage pit, but may also be connected to available sewers. If

[120] Options including dry toilets with sewered grey water belong to system groups 8 and 10 (off-site treatment of grey water).

people have their flush toilets at home, the wastewater has to be transported to an off-site treatment plant.

The third question posed in figure 6.7.2 indicates the consequences of the *rainfall regime* for the choice of either a combined or a separate sewage collection system. Separate systems can be used at any rainfall regime. Here, it should be noted that in very dry climates the scarce stormwater runoff can be transported via road surfaces and usually no stormsewers are required. Combined sewer systems are less feasible in situations with very high and irregular rainfall intensities and with a high or very low annual rainfall. The backgrounds of this screening algorithm are given above in subsection 6.4.10.

The fourth question '*Is the distance of stormwater transport short?'* determines the choice between combined and separate sewer systems in situations where for climatic reasons both systems could be feasible. If surface water is available inside or not far from the sewered community a separate system may be preferred, since the stormwater runoff can be discharged without demanding long and expensive transport pipes or channels and sanitary wastewater only has to be conveyed to the wastewater-treatment plant. The question of the maximum stormwater-runoff transport distance at which a separate system is still the preferred system can not be answered without study of the conditions in the situation under study. Long open stormwater channels could be preferred in situations with high rainfall intensities and a high risk of pollution of closed combined-sewer pipes with solid wastes, but are less feasible where there is a lack of space. In the decision to discharge stormwater runoff to surface water aspects of water quality could play a role as well: if the stormwater runoff is (locally) very polluted direct discharge is less desirable and the stormwater should be either collected in the sanitary system, or an improved separate system is preferred.

The next main distinguishing feature within the remaining clusters of system options is expressed by the question *'Has resource recovery a high priority?'* If such priority is not set, the system options arrived at are the system groups 4 (flush toilets and combined sewerage) and 6 (flush toilets and separate sewerage) with effluent discharge to surface water. If planners and decision makers consider resource recovery as a high priority, all systems can be organized in a way that various form of resource recovery are realized. Here, resource recovery can take the form of *direct agricultural reuse* of water and nutrients (system group 4 (combined sewerage) and 6 (separate sewerage) or *indirect reuse* by means of so-called clean nutrient production. Here, source-separating toilets (system groups 5, 7, 8, 9, 10, 11 and 12) are applied for obtaining concentrated waste streams for processing. The system groups 4, 5, 6 and 7 have the possibility of a centralized, large-scale lay out, while the options of the system groups 8 until 12 are more suitable for community-based drainage and sanitation.

The question *'Is agricultural reuse of effluent possible and can risks be managed'* intends to distinguish between systems in which utilization of water and nutrients in wastewater-treatment plant effluent is achieved through direct irrigation of crops, and systems in which valuable substances are recovered in another way.
The distinction between different ways of resource recovery is important, since agricultural reuse is a highly effective and direct way of effluent valorization and is far more simple than the (experimental) source-oriented systems.

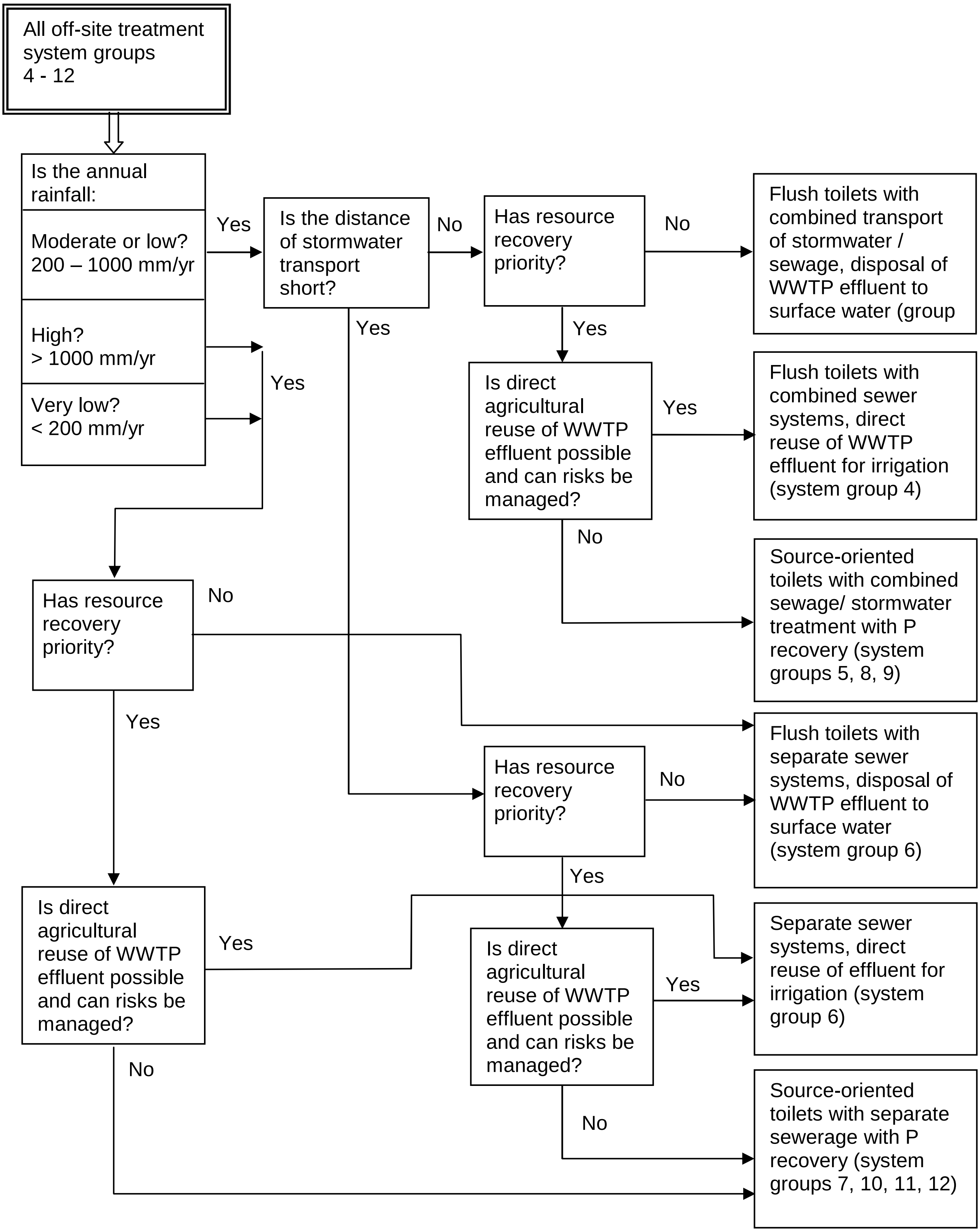

Figure 6.7.2 Decision tree for selection of off-site drainage and sanitation systems belonging to system groups 4 until 12.

Agricultural reuse presupposes a demand for irrigation water and adequate management of the risk of soil degradation and disease transmission. The need of irrigation water is greatest under climatic conditions of high temperatures and low rainfall. Often agricultural reuse presupposes storage of irrigation water either in deep surface reservoirs or as groundwater. Under conditions of a moderate rainfall regime the combined-sewerage system groups 4, 5, 8 and 9 could be applied. System group 4 comprises systems with regular flush toilets and combined sewerage and treatment of sewage and stormwater, whose effluent could be used for irrigation. The system groups 5, 8 and 9 are designed for the recovery of energy and nutrients by means of source-separation of wastewater streams. Here, system group 5 applies urine-diverting flush toilets, system group 8 urine-diverting dry toilets and system group 9 vacuum toilets for at- source separation of waste streams. In all the system groups 5, 8 and 9 grey water and stormwater runoff are transported together. It seems that the most favourable conditions for direct effluent reuse coincide with appropriate conditions for separate sewer systems as defined in this screening aid (system groups 6, 7, 10, 11, 12). It should be noted that the options of system group 4 and 5 (combined systems) and 6 and 7 (separate systems) can be used in a centralized and decentralized (community-based) way, while the groups 8 until 12 are feasible only in a decentralized (community-based) lay-out.

At this point the decision tree has made a distinction between the most appropriate conditions for systems of group 4 and 6, with and without direct reuse of effluent, and systems of the other groups with a different way of material recovery, either coupled to a combined (system groups 5, 8 and 9) or a separate sewer system (groups 7, 10, 11 and 12).

Decision trees for selection of options within the *combined sewer system groups 4 and* 5 and the *separate system groups 6 and 7* are shown in figures 6.7.3 and 6.7.4.
In these figures first the following four questions are posed:

- Do households use low volume toilets?
- Is water supply regularly interrupted?
- Is the available slope for gravity flow small?
- Are small-bore sewers used?

An affirmative answer to one or more of these questions would lead to preference of options with pre-treatment in *septic tanks* (chapter 5, system options 4C-F, 5C-F, 6C-F, 7C-F). If sewers without septic tank are used for households with low-volume toilets, interrupted water supply, low slopes of sewers and/or the use of small-bore sewers, there is a high risk of pipe clogging and thus of system failure and strongly increased maintenance costs. In Vietnamese cities often one of these conditions prevail and the use of septic tanks for solids removal is recommendable, even if the sewage is treated off-site. This leads to elimination of option 4A, 4B, 5A, 5B, 6A, 6B, 7A and 7B. The use of septic tanks presupposes the practical possibility and a functioning system of tank de-sludging, and septage treatment. Where these conditions are absent the weighing of strengths and weaknesses of septic tanks needs extra attention.

The last question in the screening aid of *combined sewer systems* (figure 6.7.3) is:

- Are high quality requirements put to discharges to surface water?

An affirmative answer to this question leads to the necessity of measures that reduce the impact of combined sewer overflows. In this case the preferred system options have retention basins for increased storage capacity (options 4B, D and F and 5B, D and F).

The distinction between plain and improved *separate sewer systems* in figure 6.7.4 is made by the question:

- Are high requirements put to stormwater discharges?

An affirmative answer to this question calls for treatment of stormwater prior to discharge in order to reduce the pollution caused by stormwater discharges. This can be realized in improved separate systems where stormwater is conveyed to the wastewater-treatment plant and untreated discharges of stormwater are allowed only at flow-rates that would lead to hydraulic overloading of the treatment plant (options 6B,D,F and 7B,D,F), or by installing a simple sedimentation facility at the end of the stormwater pipe.

A decision tree for the *source-oriented drainage and sanitation systems* seems premature, as the limited experience with these systems still does not allow sufficient insight in strengths and weaknesses of these systems. Such a decision tree therefore has not been made.

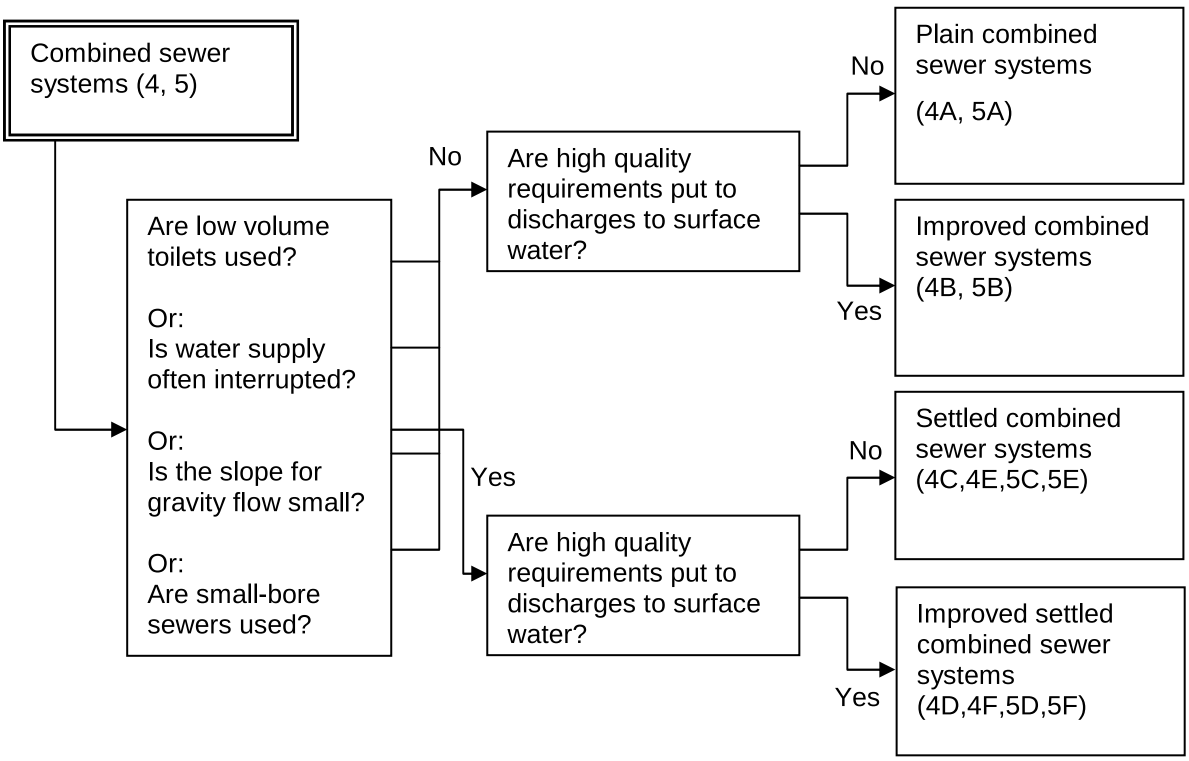

Figure 6.7.3 Decision tree for selection of options within the system groups of combined sewer systems (system groups 4 and 5).

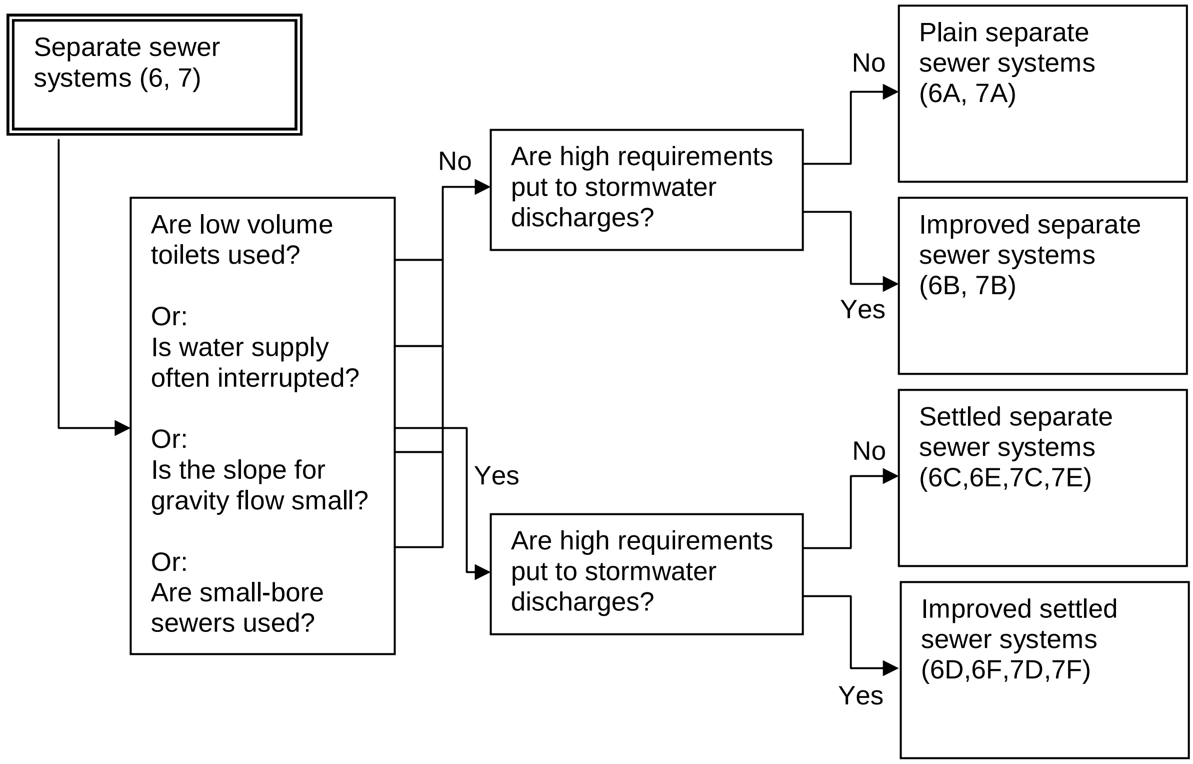

Figure 6.7.4 Decision tree for selection of options within the system groups of separate sewer systems (system groups 6 and 7).

6.8 Conclusions

In order to facilitate participatory multi-criteria decision analysis in the framework of SANCHIS processes, the present chapter 6 describes characteristics of a wide range of drainage and sanitation technologies that, in combination, form the system options inventory given in chapter 5. The technical, health-related and environmental criteria elaborated in chapter 4 are used to guide the contents of these descriptions. The main distinctions between the system options are on-site and off-site sanitation and various ways of at-source separation of wastewater streams combined with various ways of transport, treatment and resource utilization. As the SANCHIS method focuses on drainage and sanitation planning in developing countries, emphasis is laid on technologies that are applicable under the conditions of those countries.

The outcome of the present chapter are decision trees designed to select feasible and eliminate unfeasible drainage and sanitation system options for a situation under study. They are based on analysis of the restrictive factors that determine unfeasibility. The application of these decision trees in a situation under study will rarely deliver only one feasible system option, but rather a variety of feasible options. Once feasible system options have been identified, further comparison of these options may lead assessors to a ranking of options according to their appropriateness.

A drainage and sanitation system option is described here as a chain of technologies or building blocks, comprising toilets, on-site storage and treatment, transport, treatment and disposal/reuse. Within a system option there may exist various technical possibilities for the composing building blocks. The present chapter also presents a range of septic-tank, sewerage and wastewater-treatment options. For each of these different technologies their technical, health-related and environmental performances are described in order to enable the user of the data base to choose the most appropriate technology for each building block and to estimate the total performance of the chain. An example of system selection for different situations in Ho Chi Minh City and a calculation and comparison of the performances of two system options is given in chapter 10.

Appendix of chapter 6 Land use of off-site treatment stations

In the performance tables of wastewater-treatment technologies land-use data are presented. This appendix shows how these data were calculated. The land use of wastewater-treatment stations depends not only on the type of technologies used and their assumed loading rates, but also on per capita sewage generation rates, wastewater strength, size (total number of inhabitants connected and flow-rate), the surface of land used for miscellaneous structures (like service buildings and green areas within the premises of the treatment station), and land used for zoning. The latter is the width of the land surrounding a wastewater-treatment station in order to reduce nuisance to residents. In all estimations excess-sludge dewatering by means of sand-based sludge drying beds has been assumed. The land-use data for off-site treatment technologies presented in this chapter have been calculated using the assumptions listed in table A.6.1. An example of a land-use estimation for a treatment station consisting of UASB pre-treatment and trickling filter as post-treatment technology is given in table A.6.2.

Table A.6.1 Assumptions regarding calculation of land use for off-site treatment stations.

Parameter	Value
Sewage generation rate	0.16 m^3/cap.d
Size	50,000 inhabitants
Influent flow rate	8,000 m^3/d
Influent BOD_5 of mixed black and grey water	0.3 kg/m^3
Land for miscellaneous structures and green areas	2,000 m^2
Land used for zoning	0 m

Table A.6.2 Calculation of land use of a UASB-trickling filter treatment station (Influent flow rate : 8,000 m3/d, 50,000 inhabitants).

Component	Land use (m^2)
Preliminary treatment: screens and sand trap	250
UASB reactor units	593
Trickling-filter units	1,250
Secondary settler	267
Sludge thickener	8
Sludge drying beds	2,548
Miscellaneous structures	2,000
Total net surface (without zoning)	6,916
Indicative net surface per capita	0.14

The total net surface of this technology chain (without zoning) amounts to 6,916 m^2 which leads to an indicative value of the per capita land use of 0.14 m^2 . In all installations the sludge dryings beds occupy a relatively large land surface. Their assumed loading rate has been set at 120 kg TS/m^2.yr (Metcalf and Eddy Inc, 2003, p 1572). If sludge is dewatered by physical and physical-chemical methods, the land use could be significantly reduced.

CHAPTER 7 THE COST OF DRAINAGE AND SANITATION

7.1 Objective and methodology

The present chapter 7 presents a literature review of the costs of the drainage and sanitation technologies and systems introduced in chapters 5 and 6. This chapter is structured as follows. Section 7.1. introduces the objective of the chapter and methods of cost calculation. Section 7.2, until 7.8 present the cost data of respectively on-site sanitation (7.2), in-house installations (7.3), on-site storage and treatment technologies (7.4), sewerage (7.5), sewage pumping (7.6), wastewater treatment (7.7) and septage and faecal sludge treatment (7.8). Finally in section 7.9. a cost ranking of drainage and sanitation systems is proposed.

7.1.1 Objective

As expenses for infrastructure consume a significant part of household incomes, costs are an important factor in the choice of drainage and sanitation systems in addition to social, technical and environmental characteristics. Evidently, these costs depend on several local conditions, such as the status of the economy, the building density, building and environmental standards and project scale.

The aim of this chapter is to enable a comparison of costs of drainage and sanitation system options, i.e. complete systems for disposal of wastewater, including rainwater, black water and grey water, from human settlements. The system options surveyed in chapter 5 of this thesis were classified into 12 system groups, including 3 groups of on-site options (1-3), 2 groups of options with conventional flush toilets and combined and separate sewer systems (4, 6), 2 groups of options with urine-diverting flush toilets (5, 7) and 5 groups of reuse-oriented systems using the concept of source-separation (system groups 8 - 12).

7.1.2 Methods of calculation of drainage and sanitation costs per household

As noted in chapter 4 the comparison of drainage and sanitation system options with respect to economic objectives includes the notions of *life cycle costs* and *benefits from reuse.* Here, life cycle costs include the totality of incurred financial costs minus received financial benefits during the life of the drainage and sanitation infrastructure. Life cycle costs in principle include project development, promotion, construction, operation and maintenance and end-of-life measures. In most countries infrastructure costs are borne in part by the households benefiting from a system and in part by a governmental budget, i.e. by taxpayers' money. Under a regime of full privatization the households and other beneficiaries may be assumed to carry the full cost burden increased with a mark-up for management profits. In this thesis system costs are presented as if fully borne by the households. Household payments for drainage and sanitation may take the form of fees to governmental agencies, private investments in in-house installations, unpaid labour in toilet and sewer maintenance. Expenditures may be reduced through revenues associated with the selling of wastewater-related products.

According to (Kalbermatten et al., 1982) economic costing implies the application of three principles. First the cost assessment should include the costs to all involved stakeholders. In sanitation this means for example that not only the costs of infrastructure to the city authorities should be accounted for, but also the costs to the households of water use and construction of in-house installations and house connections. Second, the pricing should be based on local conditions, i.e. the situation under study. The costs of the different inputs to drainage and sanitation services (e.g. labour and mechanized equipment, but also the costs of capital) can vary widely from country to country and within countries. These differences may have an important impact on the outcomes of a cost estimation. Third, incremental rather than historical cost figures should be employed. New infrastructure may cause an upward (or downward) pressure on prices of goods and services employed in a project, so that use of prices known from previous projects could be inadequate. In addition to the implications of these general principles cost comparison of drainage and sanitation systems faces a few specific issues. First, there is the problem of *scaling variables* (Kalbermatten et al., 1982, p 52). As sanitation services are usually organized per household, the per capita costs decrease with increasing size of the household. It is evident that per capita costs of technologies from situations with different household sizes can not be immediately compared. Another factor with impact on cost estimations is the *system scale.* It is well known that, given a certain quantity of wastewater generated per capita, the costs per capita for wastewater- or sludge-treatment plants decrease with increasing plant capacity. Furthermore, there is the impact of the actual number of connections on the costs *per household*. Where the actual number of connected households is lower than the designed number, the real costs per household are higher than the costs based on designed number of connections.

According to Kalbermatten and co-authors (1982, p 54) a suitable way to compare the costs of drainage and sanitation systems that accounts for changing rates of capacity utilization is based on the calculation of the per capita Average Incremental Cost (AIC).

The per capita AIC is calculated by dividing the present worth[121] of the sum of construction costs (C_c) and recurrent (operation and maintenance) costs (C_r) and the present worth of incremental persons served:

$$AIC = \frac{\sum_{t=0}^{t=T} (C_{c\,t} + C_{r\,t})/(1+i)^t}{\sum_{t=0}^{t=T} N_t/(1+i)^t} \quad \text{(costs/household served)} \qquad (7.1)$$

$C_{c\,t}$ = system implementation costs[122] in year t (USD[123]);
$C_{r\,t}$ = recurrent (operation and maintenance) costs in year t (USD);
N_t = number of households served in year t;
i = opportunity costs[1] of capital (%/100/yr);
t = time (years);

[121] See for an explanation of the notions of *present worth* and *opportunity costs* economy textbooks such as G.J. Thuesen and W.J. Fabrycky, Engineering Economy, Prentice Hall International, 2001. Opportunity cost can be understood as the potential return (%/yr) on good alternative investment opportunities or the return that was missed, due to the investment in the project under study.
[122] Implementation costs are costs of initial realization of a project including project preparation, construction, land acquisition, etc.
[123] USD = United States Dollar.

T = design lifetime of infrastructure (years).

In the case of complete drainage and sanitation systems C_c is the sum of investments on the several parts of the chain: toilets, on-site treatment and storage, transport, treatment/reuse and disposal. In the same way also the average incremental benefits (AIB) are calculated:

$$AIB = \frac{\sum_{t=0}^{t=T} (B_{r\,t})/(1+i)^t}{\sum_{t=0}^{t=T} N_t\,/(1+i)^t} \quad \text{(benefits/household served)} \qquad (7.2)$$

Here,
$B_{r\,t}$ = recurrent benefits/revenues of resource recovery and reuse in year t (UNC).

The total annual costs per household (TACH) is then:

$$TACH = AIC - AIB \quad \text{(net costs/household served)} \qquad (7.3)$$

The TACH calculated in this way expresses the net costs of drainage and sanitation provision per household per year over the entire design lifetime of the service.

In the average incremental cost calculation the *time values* of expenses (C_c and C_r) and benefits (B_r) and the number of households (N) connected to the system come to expression. Expenses made in later years bear less heavily on the AIC value than expenses made in the first year of the project; households connected later are less important in reducing the AIC than households connected right at the start of the project. This approach is in particular important in the cost estimations per household for large-scale sewerage and wastewater treatment systems. In contrast to on-site systems where all persons in the household will use a new system right from its completion, the number of served households in sewerage schemes tend to grow gradually while most expenses are made in the beginning of the project. This adds to the financial burden of sewerage projects. The approach makes clear that an incremental (step-by-step) investment in infrastructure may reduce the costs per household.
The described method of cost estimation requires a detailed understanding of the cash flows of costs and benefits over time. Such an analysis is possible only on the basis of a technical design for a concrete situation and a scenario for the number of households benefiting from a system.

In the SANCHIS decision aid costs of systems are compared, so that *ranking* of relative costs is required rather than absolute prices, which are very much determined by time and place. Accordingly, data about relative system costs R are gathered, i.e. the costs of a system in comparison with another well-defined reference system. System costs are expressed as total annual cost per household (TACH). The simplified expression of the costs of a system option is:

$$TACH = \frac{TAC}{N} \qquad (7.4)$$

Here,
TACH = total annual costs per household (USD/hh.yr);
TAC = total annual costs (USD/yr);
N = number of households served.

The total annual net cost of the project: $TAC = AC + C_r - B_r$, so that:

$$TACH = \frac{TAC}{N} = \frac{AC + C_r - B_r}{N} \tag{7.5}$$

or:

$$TACH = AC_H + C_{rH} - B_{rH} \tag{7.6}$$

and:

$$AC = C_c * CRF = C_c * \frac{i(1+i)^T}{(1+i)^T - 1} \tag{7.7}$$

in which:
AC = annual capital costs (USD/yr);
AC_H = annual capital costs per household (USD/hh.yr)
B_r = annual recurrent financial benefits (USD/yr);
B_{rH} = annual recurrent financial benefits per household (USD/hh.yr);
C_c = construction costs (USD)
C_r = annual recurrent costs (operation and maintenance)(USD/yr);
C_{rH} = annual recurrent costs (operation and maintenance) per household (USD/hh.yr);
CRF = capital recovery factor.

The relative costs R_{A-R} of a system A as compared to reference R is found by dividing the TACH values of A and R obtained for the same conditions and time:

$$R_{A-R} = \frac{TACH_A}{TACH_R} \tag{7.8}$$

The total net annual costs (TAC) is the sum of the annual capital costs (AC), the recurrent costs (C_r) and the recurrent benefits of the drainage and sanitation project (B_r). The annual capital cost are to be understood as the costs of a loan made to pay for the project development and construction. The capital recovery factor (CRF) indicates the fraction of the invested capital (C_c) that has to be recovered annually over the entire life time T of the project at the extant values of opportunity cost (i) or minimum attractive rate of return (MARR). When comparing the cost of different drainage and sanitation chains in a certain situation at a constant value of MARR, the cost recovery factor (CRF) may bring to expression the influence of design life time on cost: a short-lived system becoming relatively more expensive than a long-lived one. Table 7.1 gives the design lifetimes assumed in this thesis.

Table 7.1 Assumed design lifetimes of infrastructure.

System	Region	Design lifetime T (yrs)	Capital recovery factor (CRF)
Individual on-site sanitation	Developing countries	20	0.080
Sewerage	Developing countries	25	0.071
Sewerage	Industrialized countries	50	0.055
Wastewater treatment	Developing countries	20	0.080
Wastewater treatment	Industrialized countries	50	0.055

Capital scarcity in developing countries leads to higher opportunity cost than in industrialized countries. Nevertheless, for the sake of the comparison, here in all calculations a relatively low MARR value of 5% has been assumed (Kalbermatten et al., 1982).
In contrast to the method of the *average incremental costs* (equations 7.1 to 7.3), the equation 7.5 may assume that the number of households served (N) is equal to the design number (N_T). over the entire lifetime of the project. Especially with sewerage and wastewater-treatment systems this procedure may lead to an undervaluation of the costs per household.
It is concluded that the base data needed for comparison of system options' costs are the costs of implementation (investment) (C_c), operation and maintenance (C_r) and the financial benefits from reuse (B_r) for various sanitation systems. The cost of system disposal at the end of the system's lifetime are neglected.

7.1.3 Construction cost (C_c)

Construction costs can be assessed on the basis of 1) calculations starting from a design and 2) data of completed projects. In this chapter both methods are used.

Calculation based on a design

In this approach a technical design with bills of quantities of required materials and labour is made and on this basis the *direct* construction costs (materials and labour) are estimated. The direct construction costs are subsequently enhanced with the indirect costs of land acquisition, site preparation, legal costs, public information campaigns, etc to obtain the total project costs. The indirect costs are usually expressed as a factor of the direct construction costs. This factor depends much on the nature and place of the works to be executed. The Dutch Sewerage Guidelines mention a figure of 66.5% for civil construction works. The same source applies a surcharge of around 90% for mechanical and electrical appliances in pumping stations bringing the overall surcharge in on the total direct cost of pumping stations to 75% (RIONED, 1997, p D1100-58). The reason for the higher surcharge are enhanced engineering and project management costs. Calculations in the Master Plan of Ho Chi Minh City assume an 80% surcharge for the indirect costs of sewerage (JICA/ Pacific Consultants International, 1999d, p I-2). The indirect costs can be strongly reduced in projects executed under community self-help, though the mobilization, training and organizational activities needed in these projects tend to somewhat diminish the savings (Hasan, 1997, chapter 2).

In this chapter the direct construction costs of septic tanks and settled separate and combined sewer systems were estimated on the basis of a detailed design using Vietnamese tables for cost of material, labour and machine deployment. The project costs, being the sum of direct and indirect costs, are subsequently estimated using a surcharge of 80% for engineering, project supervision and transaction costs.

Estimates based on completed projects
International literature is not devoid of data on the costs of drainage and sanitation systems and projects. The sources of these cost data may be very different with regard to time, place, country, climate, project size, level of material and labor costs, the cost factors included, etc. Rarely such literature data do describe adequately the system specifications, what they include and how accurate they are. Consequently, such data have little value in absolute sense, but they can be used for system comparison: the costs of several types of wastewater-treatment plants in a certain year and country mentioned by one information source can be used to determine the relative costs, i.e. the costs of system A and B in comparison to system C. It may be assumed that relative cost values (e.g. the costs of a trickling filter in relation to the costs of an activated sludge plant) are less subject to changes than absolute values and that for the purpose of system options' ranking *relative* cost figures may be sufficient. The first method definitely yields more accurate results than the second one, but it is laborious and only appropriate where the number of drainage and sanitation options compared is small (2 or 3) or the system options are simple as is the case for household on-site sanitation. Therefore predominantly the second method is used, though, as mentioned, for some technologies a full cost estimate was made.

7.1.4 Recurrent costs (C_r)
The recurrent costs of a sanitation system are the running costs at the level of the community and the household. These running costs of community systems include maintenance of structures, operation, materials, chemicals and energy and in households the costs of water consumption for flushing excreta.

7.1.5 Recurrent benefits (B_r)
To a large extent the benefits of drainage and sanitation take the form of the prevention of diseases and social discomfort and do not show on the balance sheets of the system providers. The term *recurrent benefits* (B_r) in the context of this thesis refers exclusively to products of the system that lead to financial revenues or avoided expenditures: irrigation water, soil conditioners, chemical fertilizers and biogas. Often these revenues or avoided expenditures are small in comparison to the overall system costs, but they may outweigh the costs to produce them and reduce the operation and maintenance costs of a system.

7.1.6 Economies and diseconomies of scale
As capacity of systems increases, the investment and recurrent costs *per unit* of capacity in general decline. In drainage and sanitation systems this phenomenon of *economies of scale* is negligible for the toilets, relatively small for transport technologies (sewers and cartage), but it can be considerable in wastewater treatment. Declining costs at increasing project size are associated with *indirect costs* of projects, costs of reservoirs and tanks up to a certain volume and mechanized equipment. Consequently, it is important to always take note of the scale for which a certain cost figure holds, especially for wastewater-treatment plants. There can also exist *diseconomies of scale* (increasing cost/unit at increasing capacity). They can be caused by expansion of infrastructure into areas that are difficult to service (Pernia and Alabastro, 1997) and by enhanced construction and operational risks, hindrance and safety measures connected to (very) big systems. Hence, cost considerations could lead to something like an *optimum infrastructure scale*. The issue of capacity-cost relationships is in particular relevant

in the debate of large-scale versus decentralized sanitation. The impact of capacity on costs is further elaborated on in sections 7.5.1 and 7.7.1.

7.1.7 Data bases

The costs of drainage and sanitation in this chapter are based on scientific literature, on computer software for cost estimation, reports about completed and designed projects and enquiries in Vietnam. Of particular importance are those references which have an overview of costs of several systems so that cost *ranking* may be possible. With respect to on-site sanitation the most important references are by Loetscher (1999; 1999). Cost figures of sewerage and sewage pumping come from various sources among which the Dutch Sewerage Guidelines are most detailed. Important sources of cost information about wastewater treatment are among others Alexandre et al (1998), Guerrero Erazo (2003),Oomen and Schellinkhout(1993), Qasim (1999), Somlyódi and Shanahan(1998),STOWA (1998) and the Capdetworks® (2000) computer software (Hydromantis Inc., 2000).

7.1.8 Accuracy

As this chapter shows, costs vary widely with places, years and specific site conditions. Absolute figures from one situation and time therefore have at best an indicative value for other situations and times. No attempt was made to convert prices to a base year and place for better comparison. Such an attempt requires price indexes for building and operational costs that were not available. Moreover, it may lead to a false sense of accuracy.

The used method of ranking average relative costs eliminates the influence of specific conditions to a certain degree and its results may be considered as a first approximation in the relative costs of technologies. Once this method has led to a choice of one or more feasible and cost-effective technologies for the situation under study, a cost estimation must be undertaken to validate the choice.

7.2 The costs of individual on-site sanitation

There exists a wide range of on-site sanitation systems of which a few are discussed here. Table 7.2 gives an overview of costs of these systems.

The indicated figures show that both construction and recurrent costs of sanitation systems reported in different sources vary considerably. The construction costs of urine-diverting dry toilets for example range from 90 USD (Nghien and Calvert, 2000) to 892 USD (WSP, 2009). The recurrent costs of urine-diverting dry systems include expenditures for excreta transport while the revenues from the produced vegetables are subtracted. In a study of a urine-diverting dry toilet project in Uganda the revenues from vegetables were estimated at 102 USD/household.yr, while the recurrent costs were 20 USD/hh.yr plus 90 hrs of unpaid labor (WSP, 2009, p 13).

Table 7.2 Indicative values of the costs of household on-site sanitation systems.

Sanitation system	C_{cH} (USD/hh)	C_{rH}[124] (USD/hh.yr)	TACH[125] (USD/hh.yr)
Dry accumulating anaerobic digester (DAAD)	600[126]	69[126]	117[126]
Ventilated improved pit latrine (VIP)	675[127] 258[128] 130[129, 130]	15[127] 6.7[128]	69 27[128]
Urine-diverting dry toilets	892[127] 346[128] 90[131] 160[132]	- 82[127] Negligible[128] 0 0	- 11 28[128] 7.2 12.8
Pour-flush toilet and soakage pit	248[128] 70[133]	6.7[128] 4.4[134]	27[128] 10
Pour-flush toilet plus septic tank (BW) and soakage pit	463[128] 250[132]	38[128] 10[132]	75[128] 30[132]
Cistern-flush toilet plus septic tank (BW + GW) and soakage pit	1,374[128]	72.0[128]	182[128]
Pour-flush toilet plus anaerobic digester	1,870[128]	4.4[134]	154[128]

Other sources assume that recurrent costs and revenues of urine-diverting dry toilets offset each other, resulting in a nil recurrent costs (e.g.: Loetscher (1999, p. 157). The cost overview of on-site systems made by Loetscher (1999) allows a ranking of the total annual cost per household (TACH). Estimations based on Loetscher's data show that the annual costs of the ventilated improved pit latrine, the urine diverting dry toilet and the pour-flush toilet are all in the same range (27-28 USD/hh.yr) and that the pour-flush toilet plus septic tank and soakage pit is considerably more expensive (75 USD/hh.yr), mainly due to the high costs of septic-tank desludging. The costs of sanitation for households with a cistern flush-toilet provided with septic tank for black and grey water and a soakage pit amount to 182 USD/hh.yr. About 10% of these costs are attributed to the consumption of toilet flush water. The construction costs of an anaerobic digester for joint treatment of human and animal excreta is higher than a septic tank, but the recurrent costs are lower as the benefits of reuse of gas and slurry are offsetting the maintenance costs yielding a TACH of 154 USD/hh.yr.

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[124] Assumed price of flush water: 0.2 USD/m^3.
[125] Assumed MARR: 5%; Design life time 20 years; Capital recovery factor: 0.08/yr.
[126] Calculation by author based on costs in Vietnam of transport 57 USD/hh.yr and slurry treatment 12 USD/hh.yr.
[127] (WSP, 2009). Data referring to Kabale, Uganda. Recurrent costs include VIP sludge removal and treatment.
[128] (Loetscher, 1999). Soakage pit without septic tank dimensioned for a flush flow-rate of 10 l/cap.d. Soakage pit after septic tank is dimensioned for a flush flow-rate of 20 l/cap.d and infiltration rate of 20 l/m^2.d.
[129] VIP made of indigenous material in Philippines (PHSSDA, 2007, p 55).
[130] Average VIP investment costs in Asia is 50 USD/cap (Global Water Supply and Sanitation Assessment Report 2000, cited in Hutton and Haller(2004, p 12).
[131] (Nghien and Calvert, 2000, Vietnam).
[132] (Netherlands Water Partnership, 2006, p 41). Costs in Mexico, 1998.
[133] Based on costs mentioned in Philippine Sanitation Sourcebook, 2007.
[134] Estimation by author based on water costs (Q = 10 l/cap.d; 0.2 USD/m^3) of 4 – 5 USD/hh.yr.

A comparison of the urine-diverting dry toilet (UDD) with the ventilated improved pit latrine (VIP) in Uganda showed that the construction costs of the first are higher, but that recurrent costs can be much lower or even negative, depending on the prices and yield of the agricultural crops grown on the urine and faecal matter collected from the UDD toilets. Where urine and faeces can not be reused due to a lack of nearby land, the costs of the use of the UDD toilet and the VIP are similar (WSP, 2009).

The costs of the dry accumulating anaerobic digester (DAAD) toilet, which can be seen as a non-soil-polluting version of the VIP, are considerable higher (117 USD/hh.yr) than the costs of VIP and UDD toilet, mainly due to the high costs of transport and treatment of the collected slurry. These costs strongly increase with the amount of water used for anal and toilet cleaning.

7.3 The costs of in-house installations

High-income houses with piped water supply have several in-house water-consuming installations (toilets, connections of dish-washers, washing machines, sewer plumbing, connections to the sewer lines). These constitute an important part of the total investment layout on sanitation. For high-income housing in Germany the investment costs of installations, applying cistern-flush toilets, were estimated at 2,400 USD/household on average, which is 31% of the total construction costs of sanitation (Oldenburg, 2007). The in-house installations needed for the at-source separated sanitation systems which use urine-diverting flush toilets (chapter 5, system groups 5, 7, 12) and vacuum low-flush toilets (chapter 5, system groups 9, 11) are more expensive than the regular system due to more expensive toilets and different plumbing associated with the separate collection of unwanted water. The system presented with vacuum toilets includes a kitchen waste grinder as well. Here, the in-house installations account for up to 40% of the total sanitation construction costs. An estimation of the in-house installation costs of several source-separated systems according to the system options listed in chapter 5 is shown in table 7.3.

Table 7.3 Average investment costs for in-house installations of several drainage and sanitation system options in Germany (after Oldenburg et al (2007)).

System group/ option	Description	In-house installation costs (USD/household)
6A	Cistern-flush toilets, separated treatment of stormwater and sewage (2 streams)	2,400
7A	Urine-diverting flush toilets + decentralized urine collection, separated collection of stormwater, brown/grey water and stormwater (3 streams)	3,200
11A	Vacuum toilets, separated collection of black water, grey water and stormwater (3 streams)	3,900
12A	Urine-diverting flush toilets, separated treatment of urine, brown water, grey water and stormwater (4 streams)	4,300

In developing countries these costs are usually much lower as the plumbing is simpler and building costs are much lower. As indicated in chapter 6 (section 6.2) the prices of toilets varies enormously from about 7 USD/unit for the squatting plate of a pour-flush toilet to about 800 USD/unit for a vacuum toilet[135]. The construction costs in Vietnam of in-house installations for collection of black and grey water, not including the septic tank, are about 200 USD for a two-storey house with 2 bathrooms and one kitchen [136].

7.4 The costs of on-site storage and treatment technologies

On-site sanitation technologies are on the one hand systems that provide complete excreta disposal (chapter 5, system groups 1-3) and on the other devices for the treatment of unwanted water prior to discharge into sewers (chapter 5, system groups 4 – 12). In the case of discharge into sewers usually simple primary treatment methods are applied such as septic tanks and Imhoff tanks, while discharge into surface water requires additional secondary treatment, e.g. by means of a pond or constructed wetland. This section reviews the costs of septic tanks (7.5.1). The handling of source-separated urine is discussed in subsection 7.9.3.
In this section the costs of 3 types of septic tanks are discussed: the horizontal-flow two-compartment septic tank (HFST), the UASB septic tank and the Baffled Anaerobic Septic Tank. These septic tanks can be used for the treatment of sewage, black water and grey water.

On the basis of bills of quantities of materials and labor (Department of Construction of Ho Chi Minh City, 1999) the following capacity-cost function for horizontal-flow two-compartment septic tanks was found:

$$C_{c(HFST)} = 141 * V^{0.66} \text{ (USD)} \qquad (7.9)$$

in which:
$C_{c(HFST)}$ = the construction costs of the horizontal-flow two compartment septic tank (USD)
V = gross tank volume (m^3)

The investment costs of a horizontal-flow two-compartment septic tank (HFST) made from concrete and brick with a gross volume of 2.3 m^3 amounted to 244 USD. In the tropics a tank of this volume is adequate for most households. At the daily flow-rate of 600 l/household the minimum average retention time is about 1.5 days taking into account that about one half of the tank volume is reserved for sludge accumulation.
Few data from practice are as yet available for costing household *UASB septic tanks* and *baffled anaerobic septic tanks*. For the same type of wastewater the installed tank volume per person is approximately the same as for the HFST, though by virtue of the more efficient conversion processes a higher treatment efficiency is achieved (subsection 6.2.2.2). For both alternative septic tank types at a gross volume of 2.3 m^3 the building costs are assumed to be 25% higher due to additional construction costs of the gas-solids-liquid separator (UASB septic tank) and the baffles (baffled anaerobic septic tank). Accordingly, the equation:

$$C_{c(UASB/BAST)} = 176 * V^{0.66} \text{ (USD)} \qquad (7.10)$$

[135] Squatting plate of pour flush toilet: inquiry among shops in Ho Chi Minh City in 2005; vacuum toilets: personal communication Mr B. Meulman, Landustrie, Sneek, 2009.
[136] In-house installations Vietnam: personal communication Mr Tran Van Thinh, 2009.

is used for the construction cost ($C_{c(UASB/BAST)}$) estimation of these alternative septic tank types.
Septic tanks for black water can be built somewhat smaller than for sewage as the sludge accumulation and the volumetric load are lower.
The recurrent costs (C_r) are the costs of desludging. The recurrent costs of a horizontal flow septic tank (5 – 6.25 USD/hh.yr) are calculated on the basis of desludging costs of 20 – 25 USD/tank (costs in Ho Chi Minh City in 2009) and a emptying interval of 4 years. As sludge removal costs are determined most by the frequency of desludging and to a lesser degree by the removed volume, the recurrent costs of the various septic-tank types and different types of wastewater are assumed to be equal. The estimations are summarized in table 7.4.

Table 7.4 Direct construction and operational costs for three septic tank types (indicative values in Vietnam).

Type of tank	C_{cH} USD/hh	C_{rH} USD/hh.yr
Horizontal flow septic tank for sewage (for 1 household: V = 2.3 m^3)	244[137]	5 – 6.25[138]
Horizontal flow septic tank for black water (for 1 household: V = 1.8 m^3)	208	
UASB septic tank for sewage (for 1 household V = 2.3 m^3)	305	
UASB septic tank for black water (for 1 household V = 1.4 m^3)	259	
Baffled Anaerobic Septic Tank for sewage (for 1 household: V = 2.0 m^3)	305	
Baffled Anaerobic Septic Tank for black water (for 1 household: V = 1.4 m^3)	259	

The equations 7.9 and 7.10 point at economies of scale: i.e. lower per unit costs at higher tank volumes. Accordingly, costs per household can be reduced by making several households share a communal tank. The costs could probably be reduced also by using prefab tanks.

7.5 The costs of sewerage

Sewerage is generally considered as the most expensive part of an off-site sanitation system (Serageldin, 1994). Accordingly, measures to reduce overall drainage and sanitation system cost would be most effective if targeted at the sewer system. In the present section an overview is given of construction (7.5.1; 7.5.2) and recurrent cost information (7.5.3; 7.5.4).

7.5.1 Sewerage construction costs in international literature

The actual costs of a sewer system depend on many factors, so that understandingly the cost values and functions found in literature vary considerably and can be used in an indicative way at best. Table 7.5 presents an overview of literature data on investment costs. It indicates system, investment cost, cost type, place and base year of the sewerage projects quoted. The

[137] Gross tank volume: 2.3 m^3.
[138] Tank emptying costs in Ho Chi Minh City: 20- 25 USD/tank (2009).

description of the mentioned systems is given in Chapter 6. Here, the various entries are discussed briefly.

The cost figures from the Dutch Sewerage Guidelines (RIONED, 1997) and Urban Drainage Statistics (RIONED, 2005) are based on estimates for a standardized greenfield residential area in The Netherlands. The fictitious residential area comprises 400 houses and 1040 inhabitants on a total area of 10 ha. Six ha out of these 10 ha is impervious and generates runoff. The population density amounts to 104 persons/ha. The design lifetime of the system is set at 60 years. In this area the average length of combined respectively separate sewers is 4.0 and 7.0 m per inhabitant. The estimates include 1 pumping station to lift wastewater to the main sewer lines. The investment cost of the combined sewer system (chapter 5, system option 4A) are estimated at 3,500 USD/household in 1997, while the costs had increased by about 35% to 4,700 USD/household in 2005. Based on a comparison of the replacement of an existing system with the construction of a greenfield sewer system the Dutch Sewerage Guidelines (1997) conclude that replacement is about two times as expensive as building a new system in a virgin area.

Loetscher (1999, p 152) derived an investment cost function of conventional sewerage for greenfield systems by regression analysis of project cost data from Australian towns and escalating these data to costs in USD of 1995 (equation 7-11):

$$C_{cHD} = 5.04*X*G*T*(D^{-0.35})*(5610*(H-10)^{-0.46} + 1800) \qquad (7.11)$$

Here:
C_{cHD} = construction costs per household depending on population density (USD/household);
D = population density in persons/ha;
H = number of households connected (> 10 households);
G = dimensionless factor that expresses the impact of soil nature on costs;
T = dimensionless factor that expresses impact of traffic impediment on costs;
X = dimensionless factor that expresses the relative capital costs of different sewerage types such as conventional sewerage, simplified sewerage, covered drains and settled sewerage.

On the basis of literature study Loetscher (1999) suggests the following capital cost ratios X of the various sewer systems: X = 1 for conventional sewerage, 0.43 for simplified sewerage and 0.21 for settled sewerage (septic tanks not included). G is assumed to be 1 for normal soils and 1.6 where there are excavation impediments. T equals 1, if the sewer construction causes no traffic impediments and is set at 1.33 if traffic impediments are encountered.
With the help of equation 7.11 the sewer construction costs per household as a function of project size and a population density are calculated and shown in figure 7.1 (G, T and X are 1 (standard sewer system)).

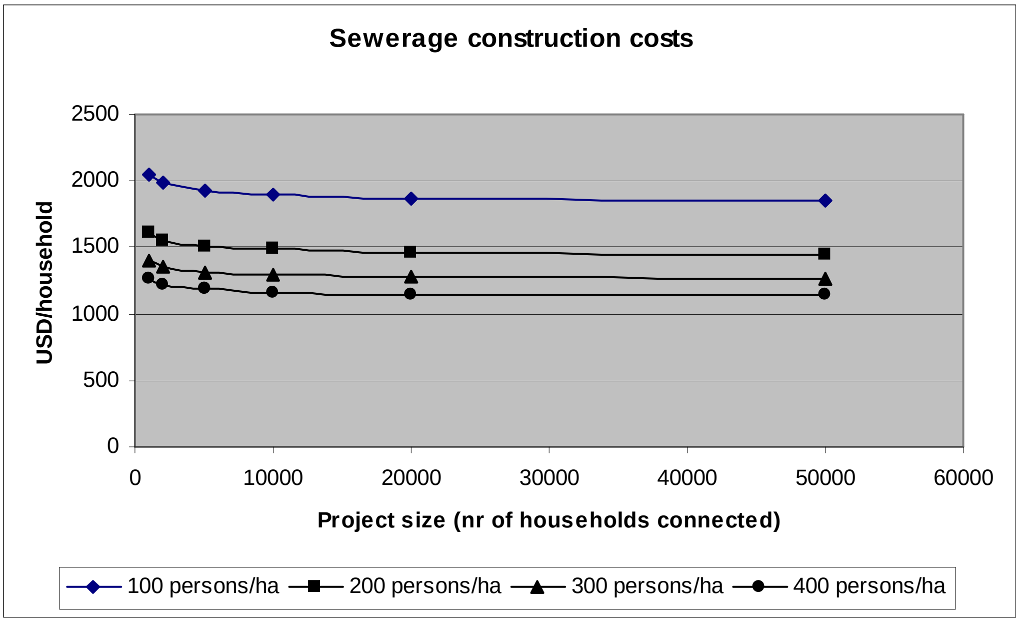

Figure 7.1 Project investment costs (USD/household) of a combined gravity sewerage system as function of project size and population density (after Loetscher(1999).

Indicative values of the investment cost (C_{cHD}) at a population density of 200/ha, a project size of 10,000 households and assuming no particular construction and traffic problems (G and T are equal to 1) are 1,484 USD/household for conventional sewerage and 638 USD/household for simplified sewerage (table 7.5).

It can be concluded from figure 7.1 that in contrast to wastewater-treatment plants, the construction costs per household hardly vary with project size: there is little cost advantage in large-scale sewerage projects. This can be readily understood from the fact that the hardware (pipes, manholes, etc) in the streets close to the houses take the largest part of the investment and that this part increases proportionally with scale. Population (building) density obviously has an important impact: the higher the building density the shorter the pipe length and the lower the sewerage investment cost per household.

Table 7.5 Construction costs (USD/household) for newly laid sewer systems in various countries and years.

Sewer system type	Construction costs for a newly laid system (USD/household)		Cost types[139]	Country	Year	Conditions	Source
	Yr 1997	Yr 2007					
Combined system Improved combined system Separate system Improved separate system Pressure system	3,500 4,100 4,500 5,300	5,100 6,000 7,200 7,500 12,400	Project, including VAT	Netherlands	1997 and 2007	Flat area, 400 houses on 10 ha in The Netherlands (new construction)	(RIONED, 1997) (RIONED, 2005) (RIONED, 2009)
Conventional sewer system Simplified sewer system Covered Drains Settled sewer system (excl septic tanks)	1,484 638 386 312		Project	Developed country (USA)	1995	Population density: 200/ha 10,000 households	(Loetscher, 1999)
Settled sewer system	150 - 500		Unspecified	Honduras	1990	Not specified	(Netherlands Water Partnership, 2006)
Condominial sewerage system	47 - 256		Construction	Brazil	1990s	22,000 households	(Melo, 2005)
Condominial sewerage system	316		Ditto	Brazil	1990s	23,000 households	(Melo, 2005)
Condominial sewerage system	256		Ditto	Brazil	1990s	45,000 households	(Melo, 2005)
Separate system	1,779		Project	Ho Chi Minh City, Vietnam	1999	New flat residential area; Population density: 396/ha	(JICA/ Pacific Consultants International, 1999d)
Combined system Settled combined system Separate system Settled separate system	807 840 871 852		Project	Ho Chi Minh City, Vietnam	2000	New flat residential area; Population density: 400/ha	(Van Buuren, 2000)
Separate system	1,865		Project	Buon Ma Thuot, Vietnam	2008	300 ha urban area; Population density: 215/ha	(People's Committee of Daklak, 2008)

[139] Project costs include costs of project development and management (see section 7.1)

In addition the table 7.5 contains construction cost data from sewerage projects in Brazilian towns in the 1990s as presented by Melo (2005) and for Honduras (Netherlands Water Partnership, 2006). In Brazil effective attempts were made to reduce the cost of sewerage through the application of the concept of condominial sewerage. In this concept the sewer system consists of two parts: the condominial and the public system. Costs are reduced by (1) laying out sewers in residential areas through backyards, frontyards and sidewalks of condominia instead of laying them in the middle of streets, (2) applying smaller pipe diameters, (3) allowing for more shallow earth covers, (4) using small inspection pits instead of large manholes and (5) making use of labor of the residents. In general the total length of sewer pipes is drastically reduced.
According to Watson (1995, p 34) a cost reduction of 20 to 60% can be reached in this way. As the figures for Brazil in table 7.5 show, the construction costs of a condominial system that connects households to the public system, are about 300 USD/household (Melo, 2005, p. 55). The costs of a condominial system are broken down as follows: 13% on the inspection chambers and boxes, 19% on material and 68% on laying the network (Melo, 2005, p 18). As these costs are estimated at approximately 60% of the total construction costs including the public system that transports the wastewater to the treatment plant, the total construction costs of sewerage for wastewater collection amounts to approximately 500 USD/household. If we compare this with the 1000 USD/household given by Serageldin (1994), a cost reduction of 50% is demonstrated.

Additional data on the relative construction costs of different construction modes are shown in table 7.6. This table demonstrates that relative costs may differ from place to place.

Table 7.6 Construction cost ratios of various sewer system types.

Conditions	Conventional sewerage	Simplified Sewerage	Settled sewerage	Source
North of Brazil 200 inh/ha, early 1980s	1	0.54[140]	-	(Mara, 1996c, p16)
Greece, 1993	1	0.23	-	(Alexiou et al., 1996)
USA (70s and 80s)	1	-	0.7	(Otis, 1996)
Colombia, 1982	1	-	0.5	(Rizo-Pombo, 1996)
Australia	1	0.43	0.21	(Loetscher, 1999)

7.5.2 Sewerage construction costs in Vietnam

With respect to the sewer system costs in Vietnam three estimates, two for Ho Chi Minh City and one for Buon Ma Thuot, are available. The first one is an estimate of the costs in Saigon East, a future section of the city, made in the framework of the Ho Chi Minh City Drainage and Sewerage Master Plan (JICA/ Pacific Consultants International, 1999d). The second is a costs estimate made by the author based on a model residential area (Van Buuren, 2000; Van Buuren et al., 2001). The third one is a recent estimate for a sewerage extension for the highland city of Buon Ma Thuot (People’s Committee of Daklak, 2008).The estimations are discussed in subsections 7.5.2.1 until 7.5.2.3.

[140] This value refers to the total annual cost per household and not capital costs.

7.5.2.1 Sewer construction cost in Saigon East.

The estimates made by Pacific Consultants International for Saigon East were analyzed in order to obtain insight in the assumed infrastructure costs in a new developed area in Vietnam. At the time of the estimate (1999) Saigon East, which encompasses district 2 and 9 of Ho Chi Minh City, had hardly any residential development and therefore could be considered as a greenfield area. In the model on which the cost estimate is based Saigon East has a *design* population of 600,000 persons, 120,000 households, a serviced area of 1,690 ha and a residential area of 1,515 ha. The average number of households per hectare is 79.2. Sewage and stormwater are to be collected separated. Before the land in this area can be used for building it has to be heightened (land filled). The overall project costs, cost per household and per hectare are summarized in table 7.7.

It can be concluded from this cost estimation that in this area the costs of land heightening (166,300 USD/ha or 16,6 USD/m^2) amount to nearly half of the total costs. This heightening is necessitated by the marshland nature of the area. The sum of investment costs of drainage and sewerage adds up to 1,779 USD/household and the costs of sewage treatment to 616 USD/household. The relatively low costs of stormwater drainage (469 + 126 = 585 USD/hh) can be ascribed to the use of a combination of pipes, canals and existing river branches for stormwater discharge.

Table 7.7 Project investment costs of drainage and sewerage infrastructure in Ho Chi Minh City- area Saigon East (after HCMC Urban Drainage and Sewerage Master Plan, PCI, 1999, part I).

Component	Costs (* 1000 USD/ha)	Costs/household (C_{cH}, USD/hh)	Fraction of total costs (%)
Land filling	166.3	2,100	46.7
Stormwater drainage	37.1	469	10.4
Sanitary sewers and pumping stations	73.3	926	20.6
Sewage treatment	48.8	616	13.7
General project costs drainage	10.0	126	2.8
General project costs sewerage	20.4	258	5.7
Total	355.9	4,495	100

7.5.2.2 Sewer construction costs in model area Saigon X 400

The estimates for a model residential area in Vietnam based on a technical design and bills of quantities refer to gravity systems in a modern, middle class, though high-density, fictitious Vietnamese urban residential area, succinctly designated as Saigon X 400 (Van Buuren, 2000). The main aim of this calculation was to find the ratios between investment costs of different drainage and sanitation system options. The design area predominantly comprises shop-houses and has a population density of 400 persons or 68 houses per hectare. It is assumed that the terrain is completely flat (gradient 0%), which of course represents a relatively difficult situation, where sewer excavation soon reaches considerable depths, but which is quite realistic in the Vietnamese delta cities. The estimation does not include the costs of sewage pumping stations. The cost estimation comprises 5 systems:

- Plain combined system (Chapter 5, system option 4A);
- Settled combined system (Chapter 5, system option 4E);

- Plain separate system (Chapter 5, system option 6A);
- Settled separate system with standard septic tank at each house (Chapter 5, system option 6E);
- Settled separate system with small interceptor tanks at each house (Chapter 5, system option 6E).

The characteristics of these systems are described in chapter 6. The houses in the combined systems are not connected directly to the stormwater lines, since this would imply the construction of many relatively big and expensive manholes in the stormwater system. Instead, the houses discharge to an inspection pit (or house connection box) and from there via a short 160 mm sanitary sewer to an inlet gully. All systems have a similar stormwater collection system with an average pipe length of 5.9 m per household and 400 m/ha.

The investment costs summarized in table 7.8 refer to new residential areas and do not include opening and repair of existing roads. For the estimation of the costs of horizontal-flow septic tanks (2.32 m^3) and the interceptor tank (0.78 m^3) the capacity-cost function $C_c = 141*V^{0.66}$ (equation 7-9) was used. The stormsewer system, with pipe diameters ranging from 0.3 – 2.0 m, was dimensioned for a design rain of approximately 360 l/ha.s (130 mm/hr) and an impermeability factor of 0.95. This design rain intensity may be expected to occur in Ho Chi Minh City with a return period of 2 years. It was assumed that the stormsewers would run under slight pressure at the design rain through filling up of inlet gullies, but overflow into the streets is avoided. The assumed domestic wastewater flow is 120 l/cap.d. The sanitary sewers of the separate systems are designed using a peak factor value of 3 and include pipe diameters between 100 and 300 mm.
The investment cost estimates of the sewer systems include direct construction cost and a project surcharge of 50% on top of the direct costs. This surcharge was not applied to the building of septic tanks since their construction is part of the house construction. The estimates were based on costing procedures of the official Ho Chi Minh City price list (Department of Construction of Ho Chi Minh City, 1999).

Table 7.8 Construction costs of sewerage alternatives in Vietnam at a building density of 68 houses/ha (author's cost estimations SaigonX 400, year 2000).

System	Unit cost of septic tank	Cost of sewer components			Total sewer system cost	
		Storm sewer	Sanitary sewer	House connections		
	(USD/hh)	(USD/hh)	(USD/hh)	(USD/hh)	(USD/hh)	(USD/ha)
Plain combined	n.a.	608	n.a.	199	807	54,750
Settled combined	246	587	n.a.	77	840	56,980
Plain separate	n.a.	587	145	140	871	59,055
Settled separate (with septic tanks)	246	587	65	80	978	66,380
Settled separate (with small interceptor tanks)	120	587	65	80	852	57,800

Table 7.8 shows that the investment costs of the five sewer systems do not differ dramatically despite their different nature and amount to 800 – 1,000 USD/household and 54,000 – 66,000 USD/ha at the given building density of 68 houses/ha. According to the applied design a non-settled separate system is only 8 % more expensive than a non-settled combined system. The construction costs of the stormwater collection grid (about 600 USD/household) constitute by far the highest fraction of the total costs and the contribution of the sanitary grid is relative small (145 USD/hh). The costs of a plain combined system were slightly higher than those of the settled combined system due to the increased excavation depth of this system (608 instead of 587 USD/household).

The biggest differences are found in the average costs of house connections between non-settled (199 and 140 USD/hh) and settled systems (77 and 80 USD/hh). The lower costs of house connections in settled systems is a consequence of the absence of coarse solids in the wastewater, so that smaller pipes can be used and the inspection/connection boxes are correspondingly smaller. In non-settled systems the house connection to the mains includes one common inspection box per 3 houses. This box has dimensions of 1.35*0.8*H (L*W*H) m, where H varies with the situation. In the settled systems two types of house connections are used: a small part of the houses has one inspection/connection box per 3 houses, but most houses are connected to the main sewers by means of shallow pipe lines at the back of the houses. This line has one small inexpensive inspection box for every two houses.
The costs of the septic/interceptor tanks in settled systems are partly offset by the lower costs of small-bore sewers and smaller gradients. In settled sewerage the use of smaller interceptor tanks instead of the standard 2.3 m^3 septic tank could lead to a slight reduction of the total costs (in Vietnam from 978 to 852 USD/household).

7.5.2.3 Sewer construction costs in Buon Ma Thuot

A drainage and sewerage extension plan has been designed for a high-density urban area of 300 ha with 65,000 inhabitants (8,390 households) in the highland town of Buon Ma Thuot in Daklak Province, Vietnam (People's Committee of Daklak, 2008). The overall direct construction costs of the separate system for this area amount to 1,219 USD/household. As the plan counts with a surcharge of 53% for indirect costs the total construction costs for drainage, sewerage and house connections are 1,865 USD/household. It has to be noted that this extension plan concerns an already built up area with a relatively low population density (215 inhabitants/ha), which makes it more expensive in principle than the greenfield plans mentioned in the previous subsections.

7.5.3 Comparison of sewerage construction costs across countries and systems

The figures of table 7.5 may give an impression of the cost differences of sewer systems in dependence of place (country), system type and mode of the construction. At the same time, the impact of local conditions, like slope of the terrain and building density, with possible important consequences to cost is not discernible in this table. It is evident that the costs in The Netherlands are many times higher than in Vietnam. While a separate system in The Netherlands was estimated at 4,500 USD (RIONED, 1997), it was estimated at 1,700 USD/household in Vietnam (JICA/ Pacific Consultants International, 1999d): a difference by a factor 2.6.

If cost-reducing construction modes are used like the condominial or simplified sewerage approach, construction costs can be brought down significantly to 500 USD/household or even less in developing countries.
There are also differences across the different sewer systems. In The Netherlands a plain separate system is estimated to be about 30% more expensive than a plain combined system. A study in Thailand demonstrated that the construction costs of a combined system were only 30% of the same costs of a separate system (UNEP, 2002, p 189). A calculation for a typical neigborhood in Vietnam showed a difference of merely 8% (table 7.8).
Most authors seem to agree that settled sewer systems are cheaper than non-settled (plain) systems. Such lower construction cost was not found in the author's estimate for Ho Chi Minh City. This may be due to the fact the stormwater system in Ho Chi Minh City, which is designed to receive high runoff flows, accounts for a much higher fraction of the total system costs than in cities in drier climates, and obviously pre-treatment in septic tanks does not lead to cost reductions in that relatively expensive stormwater drainage system.

There is a large difference between the cost estimation made in the framework of the Ho Chi Minh City Master Plan of 1999 (1,779 USD/household) and the estimation by the author for SaigonX 400 (about 900 USD/household). The difference may be explained by a higher project development and management surcharge and the inclusion of pumping stations in the estimations of the Master Plan. The costs of the 2008 drainage and sewerage plan in Buon Ma Thuot with a building density of 28 households/ha (1,865 USD/household) are in close range to the costs of the 1999 Master Plan for Saigon East (building density 79 households/ha).

7.5.4 Recurrent costs of sewerage systems in international literature

The recurrent costs of a sewerage system (C_r and C_{rH}) are expenses for inspections, cleaning, repairs and the running of sewage pumps. The data collected from various sources (table 7.9) show that on an annual basis these costs range between 0.5 and 1.0% of the construction costs.

Table 7.9 Recurrent costs of sewer systems.

Sewer system type	C_{rH} (USD/hh/yr	C_{rH} (% of C_{cH} /yr)	Source
Conventional (combined) sewerage			(Mara, 1996b, p 191)
Feeder lines	-	1.0	
Trunk sewers	-	0.5	
Combined sewerage	29	0.8	(RIONED, 1997)
Improved separate sewerage	26	0.6	(RIONED, 2002)
Conventional sewerage	2.8	0.2 - 0.4	(Watson, 1995, p18)
Condominial Sewerage	2.5 – 2.8	0.8 - 0.9	(Brazil)

This means that the recurrent costs of a system consisting of condominial feeder lines and public trunk sewers with a total construction costs of 500 USD/household would be in the range of 2.5 – 5 USD/hh.yr. The operational costs of sewer systems may rise enormously when systems are becoming old. In this situation large new investments in replacement are needed. This usually means that user charges increase suddenly at this moment in order to reach a higher recovery of capital costs from the users than before.

7.5.5 Recurrent costs of sewerage in Vietnam

The Sewerage and Drainage Masterplan of Ho Chi Minh City assumes the following percentages of the O&M costs(JICA/ Pacific Consultants International, 1999c). For the sewer lines: 0.3% of the initial costs, and 0.6% for existing neighborhoods containing old sewer lines. In the author's cost estimates an average figure for O&M costs of 0.75% is used both for combined and separate sewer systems. It may be assumed that the O&M costs for the pipelines of settled systems are lower than in non-settled systems since the septic tanks prevent to a certain extent the silting of the sanitary lines. This possible effect on maintenance costs, however, was neglected.

7.5.6 Total annual costs of sewerage

7.5.6.1 Total annual costs in The Netherlands

The total annual costs of sewerage per household are estimated assuming a design lifetime of 50 years and an interest rate of 5% yielding a cost recovery factor of 0.055. The values of construction and recurrent costs are taken from table 7.5 and table 7.9.

Table 7.10 Range of total annual costs per household (TACH) of drainage and sewerage in the Netherlands (data of 2007).

System	C_{cH} (USD/hh)	CRF (yr^{-1})	C_{rH} (% of C_{cH} /yr)	C_{rH} (USD/hh.yr)	TACH (2007) (USD/hh.yr)
Combined	5,100	0.055	0.8	41	321
Improved combined	6,000	0.055	0.8	48	378
Separate	7,200	0.055	0.6	43	439
Improved separate	7,500	0.055	0.6	45	458

7.5.6.2 Total annual costs in Vietnam

Applying the data collected in subsections 7.5.2 and 7.5.5 the total annual costs per household can be estimated. Construction costs (C_{cH}) are assumed to range from 900 to 1900 USD/household (table 7.5). Based on an assumed lifetime of 25 years and an interest rate of 5% a cost recovery factor (CRF) of 0.07 is calculated. The assumed annual recurrent costs are 0.5 (minimum) and 0.8% (maximum) of the construction costs.

Table 7.11 Range of total annual costs per household (TACH) of drainage and sewerage in Vietnam (data of period 2000 – 2008).

System	C_{cH} (USD/hh)	CRF (yr^{-1})	C_{rH} (% of C_{cH} /yr)	C_{rH} (USD/hh.yr)	TACH (USD/hh.yr)
Separate system	900	0.071	0.5	4.5	68
Separate system	1,900	0.071	0.8	15.2	150

Using the above assumptions the TACH values of a drainage and sewerage system, excluding in-house installation and treatment, in Vietnam lie between 68 and 150 USD/hh.yr.

It is evident from the figures in these tables that the recurrent costs (C_{rH}) are low as compared to the capital costs (< 10%). The costs for households in Vietnam (68 and 150 USD/hh.yr, Table 7.11) are in the order of one third to one fourth of the costs in The Netherlands (321 – 458 USD/hh.yr, Table 7.10). At a net household income in Vietnamese cities of 1,500 USD/yr

the full charge of sewerage would amount to 4.5- 10% of that income which is very high. In practice a large part of the sewerage costs is not paid by the connected household directly, but by the government (see chapter 8). The availability of international loans with a low interest rate helps to reduce interest payments and accordingly the TACH value.
It can be concluded that sewerage is an expensive system for transport of wastewater, but also that there are many ways to limit the costs by means of appropriate system choice, careful design, and users involvement in construction of parts of the system.

7.6 The costs of pumping

In sewerage systems often low-lift pumping stations have to be used. This usually is the case if the natural slope of the terrain is less than 1 : 200. In relatively small catchment areas there often is only one pumping station that lifts the water from the deepest point in the sewer to the entrance point of the treatment station from where the water travels through the station by gravity. Low-lift stations for stormwater disposal are not included in this section.In the following sections the construction and recurrent costs of pumping stations are estimated based on data for The Netherlands (7.6.1) and Vietnam (7.6.2).

7.6.1 Costs of pumping stations in The Netherlands

The construction costs of sewage pumping stations depend on several factors:

- Capacity;
- the number of pumps used (2 or 3 parallel pumps);
- the position of the pumps (submersed or dry);
- the depth of the well;
- the storage capacity of the well;
- the type of equipment used for commanding the system (telemetry);
- factors related to the building of the well.

The Dutch Sewerage Guidelines (RIONED, 2002) present capacity-cost functions based on elaborated estimates of wet-well pumping stations in the capacity range between 50 and 1,250 m^3/hr. The function abstracts from the several situational factors mentioned above and presents the dependency of costs on pump capacity only. Pumping construction cost in the Dutch Sewerage Guidelines is subdivided into three capacity brackets with each their specific capacity-cost relationships (RIONED, 1997, p D1100-22). The cost functions consist of a first term for the electro-mechanical equipment and a second term for the construction of the pump well. Table 7.12 summarizes the construction cost-capacity relationships. The total of surcharges to the direct construction cost in the estimates of the Dutch Sewerage Guidelines amount to 75%, so that the direct costs (materials and building) are 57% of the total project costs. Using these cost functions the project costs of a 75 m^3/hr pumping station are estimated at 68,450 USD, while the direct construction costs are about 39,000 USD.

Table 7.12 Construction and recurrent cost functions for sewage pumping stations in The Netherlands.

Capacity range Q (m^3/hr)	Project investment cost functions in The Netherlands (USD, 2000)	Recurrent costs in The Netherlands (USD/yr) (2000)
10-50 m^3/hr	$C_c = 4151 * Q^{0.46} + 548 * Q$	$C_r = 206 * Q^{0.54} + C_{el} * 278 * Q$
50-200 m^3/hr	$C_c = 4151 * Q^{0.46} + 8427 * Q^{0.35}$	$C_r = 206 * Q^{0.54} + C_{el} * 278 * Q$
200 – 1,250 m^3/hr	$C_c = 4151 * Q^{0.46} + 274 * Q$	$C_r = 104 * Q^{0.67} + C_{el} * 278 * Q$

The recurrent costs in The Netherlands (and Vietnam, see below) are estimated assuming annual maintenance expenditures of 5% and 2% of the investment cost of the electromechanical and the civil construction part of the pumping station respectively (RIONED, 1997, p D1100-78; RIONED, 2001, p D1100-75) and by adding the cost of energy consumption[141]. The recurrent cost functions are derived from trendlines through the cost data for two capacity brackets. The price of electricity is given as C_{el} (USD/kWh).

7.6.2 Costs of pumping stations in Vietnam

Construction and recurrent capacity-cost functions for Vietnam were derived making use of functions with the geometry of the Dutch functions (table 7.12 above) and applying a cost reduction factor of 0.32. The cost reduction factor was based on costs data from local projects (Thinh Tran V., 2009, personal communication). The resulting functions are presented in table 7.13. The reported construction costs are the project costs which include direct and indirect costs. In Vietnam a pumping station using submersible pumps with a capacity of 75 m^3/hr would cost about 22,000 USD (year 2000).

Table 7.13 Construction and recurrent cost functions for low-lift pumping stations in Vietnam.

Capacity range Q (m^3/hr)	Project investment costs in Vietnam (USD/unit) (2000)	Recurrent costs in Vietnam (USD/yr) (2000)
10-50	$C_c = 1328 * Q^{0.46} + 175 * Q$	$C_r = 65 * Q^{0.54} + C_{el} * 278 * Q$
50-200	$C_c = 1328 * Q^{0.46} + 2700 * Q^{0.35}$	$C_r = 65 * Q^{0.54} + C_{el} * 278 * Q$
200 – 1,250	$C_c = 1328 * Q^{0.46} + 88 * Q$	$C_r = 33 * Q^{0.67} + C_{el} * 278 * Q$

Assuming an electricity price of 0.1 USD/kWh in both countries, the recurrent costs of a 75 m^3/hr pumping station in The Netherlands and Vietnam would be 4,205 and 2,754 USD/yr respectively. The electricity consumption accounts for a large part of the costs of pumping stations.

7.6.3 The costs of pumping as fraction of sewerage costs

Pumping is unavoidable in long-distance sewage transport in flat areas and where borders between catchment areas must be crossed. Obviously, the costs of pumping sewage are closely related to the degree to which flow by gravity has to be supported. A calculation for

[141] The coefficient 278 in the energy term of the recurrent costs function is the slope of the trendline of the annual energy consumption as function of pump capacity Q for sewage pumps running for about 3000 hrs per year at a total head loss ranging from 9.4 to 12.2 m.

an improved separate sewer system in a fictitious Dutch extension area of 400 households showed that the investment costs of a pumping station for this area are 2% of the total costs of sewerage investment in that area (RIONED, 1997, p D1100-50).
In the case of combined sewer systems the costs are somewhat higher due to the need of heavier pumps. In The Netherlands the average costs of electricity associated with sewerage, which is mainly consumed for pumping, amount to 2.50 Euro/household.yr (3.25 USD/household.yr) (RIONED, 2001, p D1100-54). This is a very small fraction of the total average annual costs of sewerage of 172 Euro/household (RIONED, 2001, p D1100-55). It may be concluded that both the capital and recurrent costs of pumping are a (very) small fraction of the total annual costs per household of sewerage.

7.7 The costs of wastewater treatment

This section surveys the costs of wastewater treatment. The dependency of cost upon place (countries), technology and capacity is investigated. First, in subsection 7.7.1 a few details of the cost estimation of wastewater-treatment stations are given. In 7.7.2 an overview is shown of the costs of activated-sludge treatment plants across countries and capacities. Then, in subsection 7.7.3 the costs of various types of treatment plants are compared. In 7.7.4 finally a few data about wastewater-treatment costs in Vietnam are given.

7.7.1 Introduction to construction-cost estimation

Cost components
The direct construction costs of wastewater-treatment plants include water and sludge-treatment facilities and are made up of the following cost terms (Guerrero Erazo, 2003, p 86):

- purchase of land;
- preparation of the terrain;
- civil works;
- electrical and mechanical equipment;
- pipelines;
- ancillary structures and equipment .

The costs of land, civil works, and electrical/mechanical equipment are usually the most important fractions of the direct construction costs, though understandably their cost ratios depend on local conditions and the technology applied. As land costs may constitute an important fraction of the total costs of a wastewater treatment station and may vary enormously, in a comparison of technologies land costs should be mentioned explicitly. This is especially important in the case of land-intensive treatment technologies such as stabilization ponds.

Construction costs and scale
The relationship that results from the fitting of the construction costs (C_c) of wastewater-treatment stations with design capacities (Q) can be approximated by several mathematical functions such as a power function (Loetscher, 1999, p 149):

$$C_c = a * Q^n + b * C_{land} * Q^m \qquad (7.12)$$

or a binomial function (Qasim, 1999, p 1039):

$$C_c = -p * Q^2 + q * Q + r \qquad (7.13)$$

The constants a, b, n, m, p, q and r vary with local circumstances and the described technology.

In equation (7.12) the value of n varies between 0.4 and 1, in which a low value indicates strong economies of scale and the value 1 a linear increase of costs with capacity. Some backgrounds of economies of scale in wastewater treatment have been sketched in section 7.1.6.
Strong economies of scale imply that the costs per cubic meter treated decrease with increasing capacity. Values of n lower than 0.67 could be found for processes that comprise relatively expensive mechanical/electrical technology, whose costs per unit are little capacity dependent. Values of the exponent n close to unity are found in the high capacity range (e.g. above 50,000 - 100,000 PE) where treatment stations consist of a series of modules of smaller size and economies of scale are not as strong as in the lower capacity regions (Alexandre and Boutin, 1998). Practically linear capacity-cost relationships are also found over a wide range of capacities for waste stabilization ponds, constructed wetlands and soil infiltration systems for which the cost is mainly dependent on the land surface, which in its turn is proportional to the design flow-rate.

The binomial capacity-cost function (equation 7.13) expresses with its second term ($C_c = q * Q$) a linear relationship between costs and capacity. The first term $–p * Q^2$ brings to expression the deviation from linearity. Its effect on the total value of C_c increases with squared value of the capacity (Q). Accordingly, the binomial function shows the strongest deviation from linearity at high capacities. This is contrary to the experience that modular construction at the higher capacities leads to a cost increase proportional to capacity. Supposedly, the use of the binomial function stems from work on relatively large high-rate treatment stations where linear or near-to linear relationships hold. At lower capacities the same equation would not suffice.

The conclusion can be drawn, that one single power or binomial function is unable to express accurately the cost-capacity relationship for a certain treatment option over the entire range from 100 to 100,000 m^3/d. This problem could be solved by deriving capacity-cost functions that differ with capacity ranges as is also practiced with pumping stations (section 7.6).

The cost of land for wastewater-treatment stations
The cost of land is part of the investment cost of a wastewater-treatment plant and depends on the required surface (A), which in its turn is correlated with the flow-rate Q, and the local unit land cost (C_{land}). As shown in equation 7.12 the land cost can be included as a separate term in the capacity-cost equation.

The land area A required for wastewater-treatment plants consists of three terms: 1) the footprint of the treatment units of the plant, 2) the space between the treatment units and occupied by service facilities and 3) the zoning land which protects surrounding residential areas against nuisance. The first term is usually proportional to the design capacity (Q). Deviation from linearity in the capacity (Q) – land area (A) equation is mainly introduced through the need of land that is not related to the treatment proper, i.e. the land in the second and third category. The surface of this type of land tends to be relatively large in small treatment plants, so that the use of different capacity-land-use functions for small and large treatment station could be defended. It is well possible to reduce the land requirement in small treatment plants by eliminating to a high degree all land uses that are not related to the treatment process. This practice can often be seen in industrial treatment facilities, where an almost linear land-area- capacity relationship is found over a wide range of capacities.

Recurrent costs and scale
Similar to the construction costs the recurrent costs (administration, energy, chemicals, labour) per cubic meter treated decline with increasing capacity of treatment stations.

The treatment costs per household
While treatment costs are often presented as costs per cubic meter treated, in this thesis the total annual costs per household (TACH) is used, so that treatment costs can easily be added to costs of in-house installations and sewerage. The relationships between treatment costs per cubic meter (C_{Tr}), total annual costs of the treatment plant(C_c*CRF + C_r), the number of households connected (N) and the annual wastewater generation per household ($\bar{n}$ * q * 365) is described in equation 7-14.

$$C_{Tr} = \frac{C_c * CRF + C_r}{F} = \frac{C_c * CRF + C_r}{N_T * \bar{n} * q * 365} \qquad (7.14)$$

Here,
C_{Tr} = treatment costs of a treatment station (USD/m^3);
C_c = construction costs of treatment station (USD);
CRF = capital recovery factor (yr^{-1});
C_r = recurrent costs of treatment station (USD/yr);
F = cumulative annual volume of wastewater treated (m^3/yr);
N = number of households connected to treatment station (household);
$\bar{n}$ = average number of persons per household (cap/household);
q = wastewater generated per capita (m^3/cap.d).

The equation reminds us that the more households are connected to a treatment plant of a certain capacity, the lower the costs per household. Therefore, the annual costs of treatment per household (TACH) decrease at lower per capita wastewater generation rates and smaller households.

7.7.2 Costs of activated-sludge sewage-treatment stations
Since activated-sludge treatment is the most widely used sewage-treatment technology, the costs of this technology are used as a reference in the comparison with other technologies. Therefore, this section reviews data of construction and recurrent costs and cost-capacity relationships of this technology.

7.7.2.1 Costs of activated-sludge wastewater-treatment stations in international literature

Table 7.14 lists construction and recurrent costs of activated- sludge sewage-treatment plants of different capacities. Most of the mentioned systems are activated-sludge plants treating sewage from separate sewer systems (SS + AS).

Table 7.14 Construction costs, recurrent costs and TACH of activated-sludge treatment stations fed by combined (CS) and separate sewers (SS).

System	Capacity (m^3/d)	Country	Year	C_{cH} (USD/hh)	C_{rH} (USD/hh.yr)	TACH (USD/hh.yr)
SS + AS[142]	8,000	USA	1995	353	22	50
SS + AS[143]	8,000	USA	1996	481	26	64
CS + AS[144]	8,000	Netherlands	2007	695	57	114
SS + AS[145]	8,000	Netherlands	2007	478	54	93
SS + SAF[146]	500	Vietnam	2001	203	n.a.	n.a.
SS + AS[147]	108	Colombia	2003	374	22	52

There is one estimation from The Netherlands for a combined sewer system (CS + AS). In the latter case the costs of the wastewater treatment plant are higher than for separate systems due to a larger hydraulic capacity for stormwater treatment. In the calculation of the TACH value the assumed design lifetime was 20 years and the cost recovery factor 0.080.

The data suggest that strong differences of the costs per inhabitant may be expected due years of construction, place and scale. Under the adopted assumptions the TACH value of an activated sludge station for about 13,000 households in The Netherlands in 2007 was in the order of 100 USD/hh.yr.

7.7.2.2 Capacity-cost relationships

Lower costs per household at high capacities could be an argument for large scale plants. Table 7.15 presents mathematical relationships of construction and recurrent costs and design flow-rate for an activated-sludge station consisting of preliminary, primary sedimentation, aeration tank, secondary sedimentation, gravity thickening, anaerobic sludge digestion and belt press dewatering calculated by means of the data given by Qasim (1999, p 1037). A graphical presentation of these functions is shown in figure 7.2.

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142 (Loetscher, 1999, p 163); Assumed: 10,000 households.

143 (Qasim, 1999, p 1037); Assumed: 13,330 households.

144 (Wiegant, 2007); Treatment station for 70,000 PE coupled to combined sewer system. The treatment includes P and N removal.

145 (Wiegant, 2007); Treatment station for 70,000 PE coupled to separate sewer system. The treatment included P and N removal.

146 This thesis: chapter 9 and table 7.19. It has been assumed that there is no important cost difference between activated sludge (AS) and submerged aerated filter plants (SAF) at this capacity (500 m^3/d).

147 (Guerrero Erazo, 2003); Design population: 520; number of households 180.

Table 7.15 Construction costs and recurrent costs as function of capacity for activated-sludge treatment plants (capacity range 2,000 – 100,000 m^3/d).

C_c (construction costs) (USD)	C_r (recurrent costs) (USD/yr)	Source
$= -0.0007 * Q^2 + 375.3 * Q + 3 * 10^6$	$= -1*10^{-5} * Q^2 + 15.8 * Q + 214{,}702$	(Qasim, 1999)

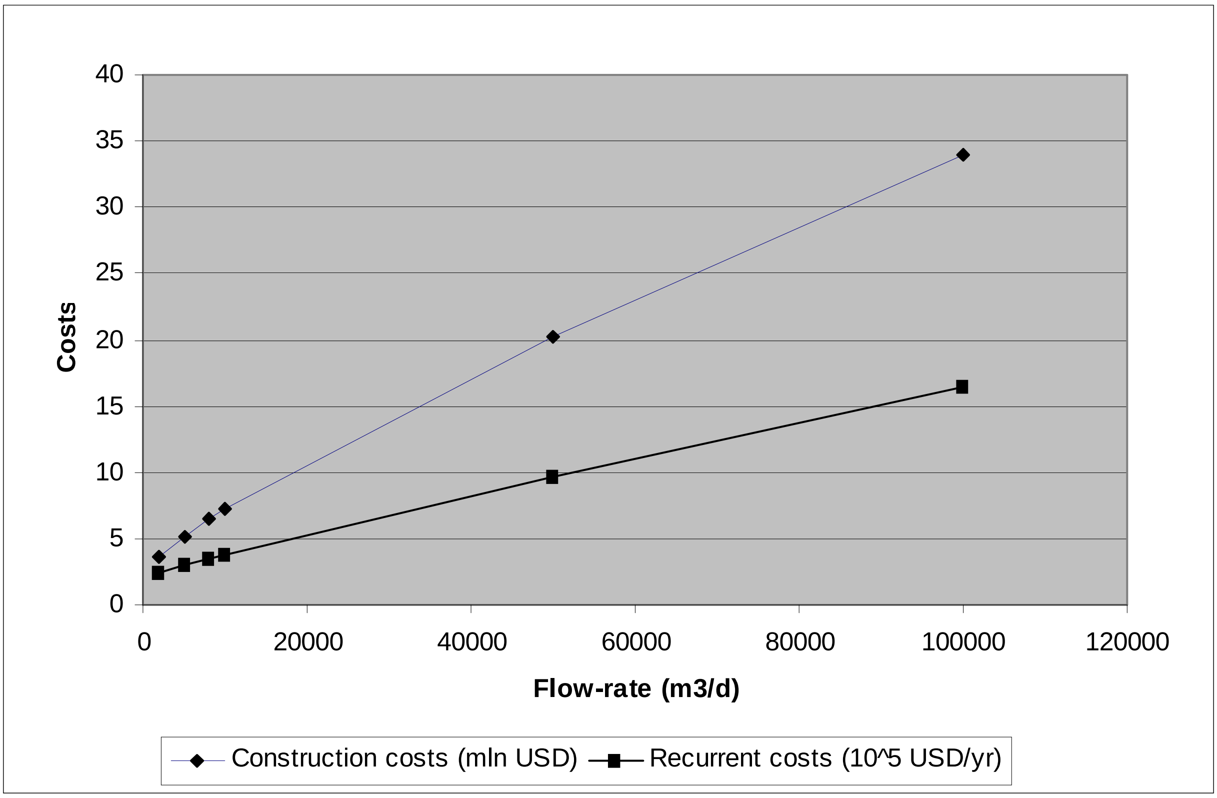

Figure 7.2 Construction and recurrent costs of activated sludge stations as function of design capacity (after Qasim, 1999).

Using the functions of construction and recurrent costs based on the data by Qasim, and assuming a wastewater generation rate of 0.6 m^3/household.d and a capital cost recovery factor of 0.08, the relationship between total annual costs per household and flow-rate is presented in figure 7.3. The graph shows the strong increase of costs of small treatment stations. This increase is mainly caused by increased construction costs per unit of capacity.

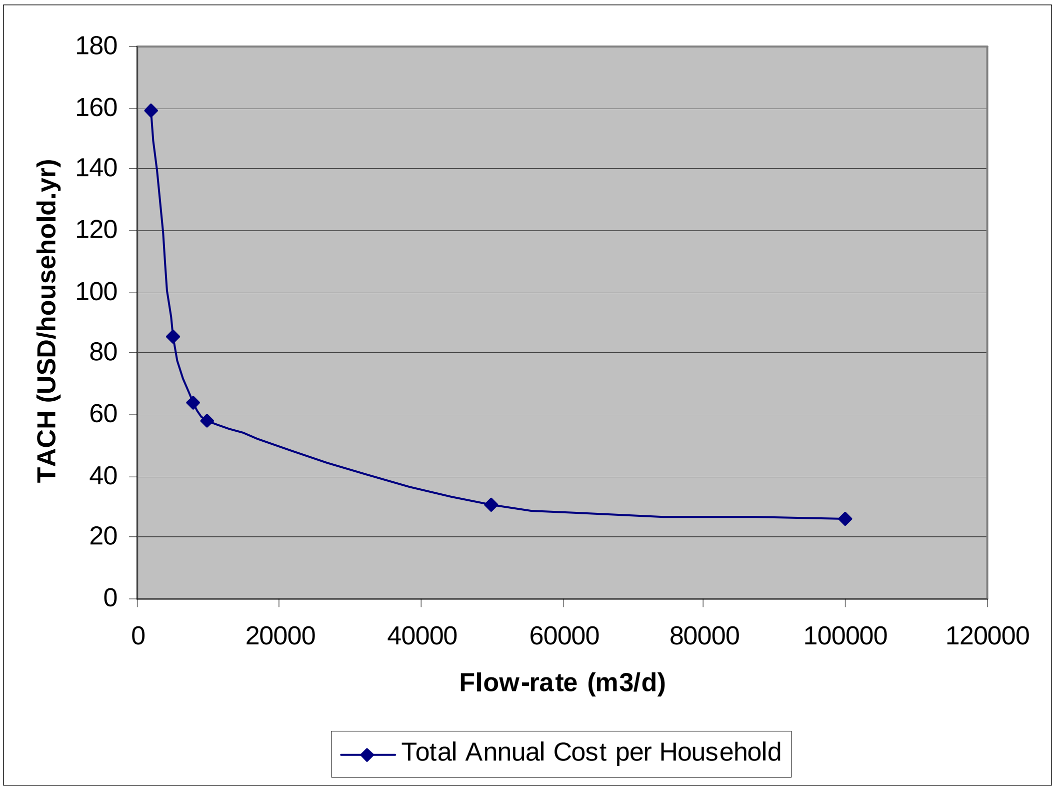

Figure 7.3 Total annual costs per household as function of design capacity for activated sludge stations (after Qasim, 1999).

7.7.3 Costs of wastewater-treatment technologies in international literature

The present section presents an overview of costs of 20 sewage-treatment technologies. Subsection 7.7.3.1 lists the technologies considered and introduces the data charts, 7.7.3.2 comments on the cost data and 7.7.3.3 discusses the cost ranking of the different technologies.

7.7.3.1 Overview of technologies considered

In order to be able to compare the costs of different sewage-treatment technologies the total annual costs per household (TACH) for 20 treatment technologies are compiled.

Table 7.18 gives an overview of the included 6 primary, 13 primary plus secondary and 1 technology train including nitrogen and phosphorus removal. As not all technologies are suitable for all treatment capacities a distinction has been made between technologies for low capacities ($\leq$ 500 m^3/d) and higher capacities (> 500 m^3/d).

The cost data are summarized in four tables in annex A.7.1:

Table A.7.1: Primary treatment at Q $\leq$ 500 m3/day;
Table A.7.2: Primary treatment at Q > 500 m^3/day;
Table A 7.3: Primary + secondary treatment at Q $\leq$ 500 m^3/day;
Table A.7.5: Primary + secondary treatment at Q > 500 m^3/day.

On the basis of the compiled construction and recurrent costs the total annual costs per household (TACH) are calculated. The assumed cost recovery factor is 8% annually. From the

TACH data relative costs of the technologies are determined and summarized in tables 7.17 and 7.18.

Table 7.16 Sewage treatment technologies included in the costs comparison.

Nr	Primary treatment
1	Horizontal flow septic tank
2	Imhoff tank
3	Primary sedimentation + sludge digestion
4	Chemically enhanced sedimentation and sludge digestion
5	Anaerobic pond
6	UASB reactor
	Primary plus secondary treatment
7	Anaerobic + Facultative ponds
8	Anaerobic + Facultative + Maturation ponds
9	Imhoff tank + Slow-rate infilration
10	Imhoff tank + Vertical flow planted filter
11	Imhoff tank + Trickling filter
12	Imhoff tank + Trickling filter + wetland
13	Imhoff tank + Rotating biological contactor
14	UASB + clarifier
15	UASB + Facultative ponds
16	UASB + Trickling filter
17	Primary sedimentation + Trickling filter
18	Oxidation ditch
19	Primary sedimentation + Activated sludge process (AS)
20	AS + N and P removal

7.7.3.2 Cost differences across time, countries and treatment plant capacities

It is evident from a comparison of the costs data of a certain technology option in tables A.7.1 until A.7.4 that the costs vary strongly across different countries, years and plant capacities. The estimated TACH values of activated-sludge stations (technology 19) with a capacity of 8,000 m^3/d vary between 28 USD/hh.yr for developing countries in the beginning of the 1990s (Oomen and Schellinkhout, 1993) until 104 USD/hh.yr (Hydromantis Inc., 2000). The recurrent costs make up a fraction of 36 – 54% of the total annual costs. Evidently, only the costs of different technologies can be usefully compared, if they refer to the same capacity, place and time. The costs ratios are more comparable, though the differences can be still large. The TACH ratios
(R) of primary sedimentation tanks with anaerobic sludge digesters (technology 3) and activated sludge stations (technology 19) for example vary between 0.35 and 0.68. The calculated average of the TACH ratios may give an indication of the costs associated with a certain wastewater-treatment technology as compared to activated-sludge treatment.

7.7.3.3 Ranking the costs of wastewater-treatment plants

The ranking of wastewater-treatment costs is assessed using the average TACH ratios R and converting these ratios to a value on a scale 0-10 , where 0 corresponds to expensive high total annual costs per household of 1.5 times the average TACH of an activated sludge treatment plant and 10 to a imaginary free treatment plant with TACH = 0. These TACH scores are given at the bottom line of the tables 7.17 and 7.18.

It can be concluded from table 7.17 that among the primary plus secondary wastewater treatment technologies 7 – 20 *for capacities smaller than 500* m^3/d relatively low TACH values (high scores) are found for anaerobic and facultative ponds (technology 7) and the UASB reactor plus clarifier (technology 14). Their TACH values are 50 – 60% of the costs of an activated sludge plant (technology 19). The costs of ponds are of course to a high degree determined by the price of land. The combinations of Imhoff tanks and post-treatment methods (technologies 9 – 13) are found to be in the order of 75 –90% of the TACH of activated sludge plants. The construction costs of a septic tank plus anaerobic upflow filter, which is not listed in these tables, are about 1.5 times higher than the UASB reactor (Von Sperling, 1996). Planted filters or open surface wetlands may be a good secondary treatment technology for small treatment plants, where space is available and high requirements are put to the effluent concentration (technologies 10 and 12).

For primary plus secondary treatment plants with a *capacity larger than 500* m^3/d the UASB reactor with facultative post-treatment ponds (technology 15) is the least expensive option. Its TACH value is approximately 60% of the costs of activated-sludge treatment. If little space is available, the best option would be the UASB reactor plus trickling filter (technology 16). This technology train combines low costs (about 70% of the costs of activated-sludge treatment) with a good effluent quality (BOD_5 < 20 mg/l).

Table 7.17 Summary of total annual costs per household (TACH) and TACH ratios R for various wastewater-treatment technologies (activated sludge process =1.0) (Q $\leq$ 500 m^3/d).

Technology	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Effluent BOD_5	mg/l	210	210	210	100	150	75	35	20	20	20	35	20	35	60	35	20	35	20	20	10
Alexandre	TACH		39.2					67.0		101		102		117					130		
	R		0.30					0.50		0.75		0.76		0.87					0.97	1	
Guerrero-E.	TACH							45.6			46.6		39.2		27.5				68.5	52.4	
	R							0.87			0.89		0.75		0.52				1.30	1	
Loetscher	TACH	22.9	48.1					54.4												162	
	R	0.14	0.30					0.34												1	
	R aver.	0.14	0.30					0.57		0.75	0.89	0.76	0.75	0.87	0.52				1.14	1	
Score (0 – 10)		9.1	8.0					6.2		5.0	4.1	4.9	5.0	4.2	6.5				2.4	3.3	

Legend of Technologies.

	Technology		Technology
1	Communal horizontal flow septic tank	11	Imhoff tank + Trickling filter
2	Imhoff tank	12	Imhoff tank + Trickling filter + Wetland
3	Primary sedimentation tank + Sludge digestion	13	Imhoff tank + Rotating biological contactor
4	Chemically enhanced sedimentation + Sludge digestion	14	UASB + Clarifier
5	Anaerobic pond	15	UASB + Facultative pond
6	UASB reactor	16	UASB + Trickling filter
7	Anaerobic + Facultative ponds	17	Primary sedimentation tank + Trickling filter
8	Anaerobic + Facultative + Maturation ponds	18	Oxidation ditch
9	Imhoff tank + Slow-rate infiltration	19	Primary sedimentation + Activated sludge process
10	Imhoff tank + Vertical flow planted filter	20	Activated sludge process with N and P removal

Table 7.18 Summary of total annual costs per household (TACH) and TACH ratios R for various wastewater-treatment technologies (activated sludge process =1.0) (Q > 500 m3/d).

Technology	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Effluent BOD_5	mg/l	210	210	210	100	150	75	35	20	20	20	35	20	35	60	35	20	35	20	20	10
Arthur	TACH								10.1									16.4	14.7		
	R								0.67									1.08	0.97		
Hydromantis	TACH			56.6															68.5	104	120
	R			0.54															0.66	1	1.15
Loetscher	TACH							32.5												48.0	
	R							0.68												1	
Oomen & S.	TACH			11.1		6.5	10.5	19.0								15.5	19.2		27.0	27.7	
	R			0.40		0.23	0.38	0.69								0.56	0.69		0.97	1	
Qasim	TACH			22.5																64.0	
	R			0.35																1	
STOWA	TACH			22.8																44.6	63.1
	R			0.51																1	1.41
Somlyódi & S.	TACH			35.5	43.4															52.1	90.8
	R			0.68	0.83															1	1.74
	R aver.			0.53	0.83	0.23	0.38	0.68	0.67							0.56	0.69	1.08	0.97	1	1.43
Score (0 –10)				6.5	4.5	8.5	7.5	5.5	5.5							6.3	5.4	2.8	3.5	3.3	0.5

Legend of technologies

	Technology		Technology
1	Communal horizontal flow septic tank	11	Imhoff tank + Trickling filter
2	Imhoff tank	12	Imhoff tank + Trickling filter + Wetland
3	Primary sedimentation tank + Sludge digestion	13	Imhoff tank + Rotating biological contactor
4	Chemically enhanced sedimentation + Sludge digestion	14	UASB + Clarifier
5	Anaerobic pond	15	UASB + Facultative pond
6	UASB reactor	16	UASB + Trickling filter
7	Anaerobic + Facultative ponds	17	Primary sedimentation tank + Trickling filter
8	Anaerobic + Facultative + Maturation ponds	18	Oxidation ditch
9	Imhoff tank + Slow-rate infiltration	19	Primary sedimentation + Activated sludge process
10	Imhoff tank + Vertical flow planted filter	20	Activated sludge process with N and P removal

7.7.4 Sewage-treatment costs in Vietnam

7.7.4.1 Construction costs of sewage treatment in Vietnam

Since the year 2000 a large number of small and a small number of large sewage treatment stations have been built in Vietnam. Some of the available data about construction costs are reviewed in table 7.19. The data of the small plants are derived from the survey undertaken in the framework of this thesis reported in chapter 9. The cost of these plants are all converted to US dollars for the year of completion of the construction. In each of the presented stations, except the station of Binh Hung Hoa, the sewage is transported by means of a separate system.

Table 7.19 Construction costs of sewage-treatment stations in Vietnam.

Name sewage treatment plant	Design capacity (m^3/d)	Design population	Design nr of households	Treatment technology	Construction cost (C_c) (mln USD, year)	Construction cost per hh (C_{cH}) (USD/hh)
Tan Quy Dong, Ho Chi Minh City[148]	500	3,000	620	SAF	0.126 (2001)	203
Agromarket Thu Duc[149]	1,500	n.a.	n.a.	SED + AS	0.320 (2003)	n.a.
Buon Ma Thuot (Extension phase)[150]	4,825	38,600	5,180	WSP	4.70 (2008)	789
Da Lat[151]	7,500	66,500	13,300	SED + TF	3.43 (1999)	258
Binh Hung Hoa, Ho Chi Minh City[152]	45,000	160,000	32,000	Aerated Lagoon and WSP	13.02 (2006)	407

The number of data in this table is too limited and their nature too diverse to draw conclusions about the relationship between capacity and construction costs. The construction costs vary between 203 USD/household in the case of the Tan Quy Dong Plant (2001) to 789 USD/household for the Buon Ma Thuot plant (2008). For the Binh Hung Hoa aerated lagoons plus ponds (C_c = 407 USD/household) in Ho Chi Minh City 77% of the investment was spent on acquisition of land (based on data from Verschure and co-authors(Verschure et al., 2006, p 12). The survey of small public-commercial wastewater-treatment plants presented in chapter 9 of this thesis shows a linear relationship between capacity and costs across the various

148 This thesis, chapter 9: 620 households .
149 This thesis, chapter 9: wastewater of a wholesale market.
150 (People's Committee of Daklak, 2008): estimated direct construction costs including 15% contingencies.
151 Estimated direct cost calculation in 1999. The plant was completed in 2004.
152 (Verschure et al., 2006): project costs: 2.305 mln + 7.713 mln for land acquisition = 10.018 mln Euro = 13.02 mln USD (1 Euro = 1.3 USD).

treatment technologies over a capacity range of 40 – 1,500 m^3/d and an construction costs range of 94 – 432 USD/m^3/d. It may be concluded that the actual construction costs of a municipal secondary wastewater-treatment plants in Vietnam under the reigning effluent requirements are in the order of 50 to 125 USD/inhabitant and 400 – 800 USD/household.

7.7.4.2 Recurrent costs of sewage treatment in Vietnam

The survey of small sewage-treatment plants (chapter 9) has shown that the recurrent costs of secondary sewage-treatment plants in a capacity range of 40 – 1,500 m^3/d treating low strength public-commercial wastewater were 0.05 – 0.22 USD/m^3 treated (2007). If a recurrent cost of 0.15 USD/m^3 treated and a per household sewage flow-rate of 0.6 m^3/d (219 m^3/hh.yr) is assumed, the operational cost of secondary sewage treatment would be approximately 33 USD/household.yr.

7.7.4.3 Total annual costs per household of sewage treatment in Vietnam

Assuming a construction cost of a sewage-treatment station of 800 USD/household[153], a capital recovery factor of 0.08, and a recurrent cost of 33 USD/household.yr, the total costs of secondary sewage treatment (TACH) in Vietnam would be 97 USD/household/year.

7.8 The costs of septage and faecal sludge treatment

The costs of sludge stabilization and dewatering are included in the estimations of the costs of municipal wastewater treatment as presented in section 7.7. The further transport and treatment of bio-solids also contributes to the costs to a small degree but is not included. As septic tanks are an element in many of the drainage and sanitation options the costs of treatment of the sludge collected from these tanks is briefly mentioned here. According to Heinss (1999), quoted in Montangero and Strauss (2002), the costs of septage treatment by means of a constructed wetland amounts to 130 USD/tonne TS, which would be 3.25 USD/m^3 at a TS content of septage of 25 kg/m^3. As the solids from septage can be reused as soil conditioner, a part of the treatment cost can usually be recovered. In Ho Chi Minh City in 2006 the market price of soil conditioner from septage was about 50 USD/(wet) tonne.

7.9 Ranking drainage and sanitation system costs

In this final section a ranking of the drainage and sanitation systems costs is given. The preceding sections showed that costs depend on many local factors, among which system scale, building density and rainfall conditions are of primordial importance. Also the rate of interest on borrowed capital plays a decisive role. As the presented ranking is derived from several sources, it has a mere indicative quality.

7.9.1 Comparison of on-site systems

A comparison of the costs of several on-site systems, expressed as total annual costs per household, can be made on the basis of table 7.2. From the least expensive to the most expensive on-site systems the order is as follows:
(1) urine-diverting dry toilets (-11 and 28 USD/hh.yr), (2) pour-flush toilet and soakage pit (10 and 27 USD/hh.yr), (3) ventilated improved pit latrines (27 and 69 USD/hh.yr), (4) pour-flush toilet plus septic tank and soakage pit (30 and 75 USD/hh.yr), (5) dry anaerobic

[153] The estimated construction costs of the Buon Ma Thuot plant (2008) is 789 USD/household.

accumulating digester (117 USD/hh.yr), (6) pour-flush toilet plus (continuous flow) anaerobic digester (154 USD/hh.yr) and (7) cistern-flush toilet plus septic tank and soakage pit (182 USD/hh.yr). These costs are all lower than the costs of an off-site system consisting of cistern-flush toilets and other in-house installations connected to a sewer system and activated-sludge wastewater-treatment plant (Loetscher, 1999, p 159). The table 7.20 below shows that the total annual costs per household of the Buon Ma Thuot drainage and sanitation system in Vietnam (capacity: 4,825 m^3/d) were estimated at 247 USD/hh.yr.

7.9.2 Comparison of various off-site systems

The relative fraction of costs of collection and transport (sewerage) as compared to wastewater treatment can be derived from table 7.20.

Table 7.20 Indicative cost values of sewerage and wastewater treatment (TACH)

System option	Place	Year	TACH Sewerage (USD/hh.yr)	TACH WWTP (USD/hh.yr)	TACH System (USD/hh.yr)
4A Combined	Netherlands[154]	2007	321	114	435
6A Separate	Netherlands[154]	2007	439	93	532
6F Improved Separate	Netherlands[154]	2007	458	100	558
6A Separate	Vietnam[155]	2008	150	97	247

The TACH values for sewerage and wastewater treatment in The Netherlands are in the proportion of between 4.6 : 1 and 3 : 1. The figure for Vietnam shows lower relative costs of sewerage. Wastewater-treatment plants treating influent from separate systems are not subject to the strong flow fluctuations caused by stormwater. Accordingly, the costs of these treatment plants can be somewhat lower and the effluent quality is more constant. Sewerage in Vietnam is less expensive than in The Netherlands due to the lower price level of construction and a higher building density. The relatively high annual costs per household of treatment in Vietnam are due to the large size of the households (about 6 persons), so that the costs have to be shared by a relatively small number of households. As capital recovery on construction costs of sewerage accounts for the highest contribution to the total annual costs per household, the most important measure to lighten the financial burden is reduction of sewerage construction costs.

The ranking of costs of sewered sanitation and drainage systems, i.e. the systems of group 4 (combined systems) and 6 (separate systems), is determined by the applied technologies and possibilities of the intervention zone.

First, the order of sewer technologies from the least to the most expensive is as follows: plain combined (system option 4A), improved combined (system option 4B), plain separate (system option 6A), improved separate (system option 6B), pressure sewers (table 7.10). As per the cost analysis given in the Dutch Sewerage Guidelines two-pipe systems are more expensive than one-pipe systems.

[154] Based on data from RIONED (2009) and an estimation by Wiegant (2009) (tables 7.10, 7.14 and section 7.7.2.1) (Scale: 8,000 m^3/d).

[155] Based on data for Buon Ma Thuot City (separate sewer system with waste stabilization ponds) (tables 7.11 and section 7.7.4.3) (Scale: 4,825 m^3/d).

Second, the costs of stormwater as compared to sanitary wastewater transport will increase at higher rainfall intensities. This leads to smaller cost differences between one and two-pipe systems at higher design rainfall intensities. Important cost reductions can be achieved by uncoupling of stormwater from the drainage system and by diminishing the transport distance for storm water. Accordingly, plain separate or settled separate systems (options 6A and 6C) could become less expensive than combined systems where the stormwater-drainage system size can be reduced.
Third, the costs of any type of sewerage can be significantly reduced by applying the concept of condominial or simplified sewerage (table 7.5). The influence of on-site removal of solids from wastewater on system costs depends on the situation under study. Pre-settling allows for less expensive small-bore pipes, but requires the construction and maintenance of a septic tank. Otis (1996) and Rizo-Pombo(1996) claim an important cost reduction (table 7.6), but estimations for Ho Chi Minh City by the author do not point at lower costs for the settled sewerage system (table 7.8). It is concluded here, that the price difference between settled and non-settled sewer systems is negligible.
Fourth, with regard to wastewater treatment, in particular in a tropical climate, there are technologies which combine a high treatment efficiency with reduced costs (tables 7.17 and 18). UASB-pretreatment with trickling filters as post-treatment is an example in case.

7.9.3 Comparison of reuse-oriented sanitation systems

Reuse-oriented systems yield products such as nutrient solutions from urine, phosphate salts and biogas. In this respect they are different from the sanitation systems that just treat wastewater. In addition, they may reduce water and energy consumption and the costs of kitchen waste disposal. The question is to what degree the financial revenues of products and savings counterbalance the costs of system modifications that facilitate reuse. Similar to all cost estimations this financial comparison is time-dependent, but an extra factor is the role of externalities. For example: with respect to the production of reusable biogas the current market value of this gas is put on the balance sheet, but not the value connected to the reduction of greenhouse gases. Putting these benefits on the balance would improve the attractiveness of reuse-oriented system options.

A first source of cost data on reuse-oriented systems are studies by Oldenburg and co-workers (2007; 2007). The systems described in these publications correspond to the system options 6A, two versions of option 7A that differ with respect to the mode of transport of urine to the land, option 11A and option 12A mentioned in chapter 5. The costs estimations in this work apply to a low density community in Germany with 2,040 households (4,891 persons). The cost data are given in table 7.21.

Table 7.21 Indicative total annual costs per household (TACH) of conventional and reuse-oriented sanitation systems (after Oldenburg and co-authors(2007)). Construction costs (C_{cH}) include in-house installations, transport and treatment. Drainage is excluded. Scale: 2,040 households. Exchange rate USD/Euro = 0.74.

System option	Drainage and sanitation system	Annuitized C_{cH} (USD/hh.yr)	$C_{rH} – B_{rH}$ (USD/hh.yr)	TACH (USD/hh.yr)
6A	Regular flush toilets, gravity sewer system with aerobic wastewater treatment	350	522	872
7A	Urine-diverting flush toilets, urine transport by pipe, sewerage with aerobic brown + grey water treatment, composting of sludge and biowastes	470	443	913
7A	Urine-diverting flush toilets, urine transport by cartage, sewerage with aerobic brown + grey water treatment, composting of sludge and biowastes	425	431	856
11A	Vacuum toilets, separated collection of black and grey water, anaerobic treatment of black water + biowastes, and aerobic grey water treatment	451	444	895
12A	Urine-diverting flush toilets, separate collection of urine, black and grey water, aerobic grey water treatment, composting of faecal sludge, grey water sludge and biowastes	530	456	986

The described systems include in-house installations, transport and treatment of wastewater and domestic biowastes, but exclude stormwater drainage. Source-separated urine is supposed to be stored and used on agricultural land without further treatment. Domestic biowastes are co-composted or co-digested.

The TACH values of the described sanitation systems (872-986 USD/hh.yr) are relatively high in comparison with systems reported by other authors (e.g. Loetscher(1999) and Wiegant (2007)), mainly due to the small scale (2,040 households) of the model zone.

The urine yield in the modeled community associated with the urine-diverting flush toilets (option 7A) is estimated at 2,008 m^3/yr with a market value of about 5,000 USD/yr (2.45 USD/hh.yr)[156]. The value of the produced compost (325 m^3/yr) in the system groups 7 and 12 amounts to 26,400 USD/yr (12.9 USD/hh.yr) and the benefit of flush-water saving to 36 USD/hh.yr. Accordingly, the recurrent benefits (B_{rH}) of the urine-diverting system are the sum of the benefits of collected urine, compost and water saving which is about 51 USD/hh.yr.

[156] The modelled community counts 4,891 inhabitants of which 75% uses the urine-diverting toilets. The collected urine from those who use the UD toilets amounts to 1.5 l/cap.d. The market value of urine is assumed to be 2.61 USD/m^3.

The value of the electricity produced from biogas in the option (11A) with vacuum toilets and anaerobic digestion of concentrated black water and biowaste is estimated at about 45,000 USD/year (22 USD/hh.yr) and the value of the saved water at 36 USD/hh.yr, so that the total recurrent benefits (B_{rH}) of vacuum-toilet sanitation would be 58 USD/hh.yr.

The TACH values of the system options with urine-diverting flush toilets (7A) and vacuum toilets (11A) (856 USD/hh.yr respectively 895 USD/hh.yr) are not much different from the TACH of the conventional separate system with cistern-flush toilets (system option 6A, 872 USD/hh.yr). Apparently, under the chosen conditions the costs of a urine-reuse system are not higher than those of a conventional system. The costs of a vacuum-toilet based system are only slightly higher than the costs of a conventional system.

A second source of cost data is a report by Royal Haskoning (Wiegant, 2007), in which medium and small-scale conventional gravity sewered systems (option 4A) were compared with medium-scale systems with urine-diverting flush toilets (option 5A) and small-scale systems with vacuum toilets and separate treatment of black and grey water (option 11A). In terms of the systems numbering in chapter 5 of this thesis these are the system options 4A, 5A and 11A. The assumed design capacities of the medium-scale and small-scale systems were 70,000 and 4,600 PE (30,435 and 2,000 households) respectively. These data had to be made comparable with those of Oldenburg (table 7.21) by adding costs of in-house installations and combined transport of grey water and stormwater. The costs of in-house installations were borrowed from Oldenburg (2007) and the costs of wastewater transport of Sewerage Statistics (RIONED, 2009). The construction costs of small and medium scale combined sewer systems were assumed equal (5,100 USD/household), though data presented by Loetscher (1999) show slightly higher construction costs in smaller projects (figure 7.1). Differences with the work of Oldenburg (2007) are among other things the assumptions of combined sewerage and the treatment of wastewater and sludges. In the study by Wiegant excess sludges are dewatered and incinerated and not reused as in the estimations of Oldenburg. The results of the synthesis made on the basis of the Royal Haskoning report are presented in tables 7.22 and 7.23.
The financial benefits of lower water consumption and benefits of energy savings associated with the reuse-oriented systems 5A and 9A have been accounted for in the recurrent costs (C_r) of in-house installations and treatment respectively.

Tabel 7.22. Gross costs of sanitation systems (1 household = 2.3 persons; 0.74 E/USD).

System option		Two regular flush toilets per household, central combined sewerage, aerobic tertiary treatment, no sludge digestion	Two regular flush toilets per household, de-central combined sewerage, aerobic tertiary treatment, no sludge digestion	Two urine-diverting flush toilets per household, combined sewerage, aerobic tertiary treatment, no sludge digestion. Urine separation and struvite recovery	Two vacuum toilets and kitchen waste grinder per household, de-central separated transport and treatment of black water and grey water + stormwater. Kitchen waste co-digestion
System nr		4A	4A	5A	9A
Inhabitants	Number	70,000	4,600	70,000	4,600
Households	Number	30,435	2,000	30,435	2,000
In-house					
C_{cH}[157]	USD/hh	2,400	2,400	3,200	3,900
C_{rH}[158]	USD/hh.yr	43	43	8	9
TACH	USD/hh.yr	213	213	255[159]	321[160]
Transport					
C_{cH}	USD/hh	5,100[161]	5,100	5,300[162]	6,100[163]
C_{rH}	USD/hh.yr	40.5	40.5	48[164]	50[165]
TACH	USD/hh.yr	321	321	348[166]	410[167]
Treatment					
C_{cH}	USD/hh	695	1,820	691	2,230[168]
C_{rH}	USD/hh.yr	57	112	56	122[169]
TACH	USD/hh.yr	114	307	114	327[170]
TACH total	USD/hh.yr	648	841	717	1,058

157 Investment cost data from Oldenburg (2007; 2007). Capital Recovery Factor = 0.071.
158 Costs of water consumption. Standard water consumption 34.5 l/cap.d. Water price: 1,1 Euro/m^3 (= 1,5 USD/m^3). System options 5A and 9A lead to considerable reduction of drinking-water consumption.
159 TACH = 2,400 *0.071 + 800 * 0.096 + 8 = 255 USD/hh.yr.
160 TACH = 3,900 * 0.08 + 9 = 321 USD/hh.yr
161 Investment cost data of combined sewer system from Dutch sewerage statistics (RIONED, 2009). Capital recovery factor = 0.055.
162 Investment costs of combined system (brown water and rainwater): 5,100 USD/hh; investment costs of extra provisions for urine transport: 216 USD/hh (160 E/hh), rounded off at 200 USD/hh.
163 Investment including vacuum transport of black water and combined gravity sewerage of grey and stormwater.
164 Operational costs of transport of sewage: 40.5 USD/hh.yr. Extra costs of separate collection of urine: 5.30 Euro/hh.yr (= 7.2 USD/hh.yr) (Wiegant, 2007, p 18).
165 Estimate by author.
166 TACH = 5,100 * 0.055 + 200 * 0.096 + 48 = 348 USD/hh.yr.
167 TACH = 5,100*0.055 + 1000*0.08+ 50 = 410 USD/hh.yr.
168 Construction costs of black water treatment plant (4,600 PE): 855 USD/hh. Construction costs of grey water and stormwater treatment: 1,375 USD/hh. Total construction costs: 2,230 USD/hh.
169 Operational costs of black water treatment: 67 USD/hh.yr. Operational costs of grey water treatment: 55 USD/hh.yr. Total operational costs: 122 USD/hh.yr. Energy savings and biogas production were accounted for in these figures (Wiegant, 2007, p 11 and 16).
170 TACH = 855 * 0.088 + 1375* 0.094 + 122 = 327 USD/hh/yr.

Table 7.23 Total annual costs per household of the sanitation systems. Price level 2007 (based on Wiegant (2007)).

		Two regular flush toilets per household, central combined sewerage, aerobic tertiary treatment, no sludge digestion	Two regular flush toilets per household, de-central combined sewerage, aerobic tertiary treatment, no sludge digestion	Two urine-diverting flush toilets per household, combined sewerage, aerobic tertiary treatment, no sludge digestion. Urine separation and struvite recovery	Two vacuum toilets and kitchen waste grinder per household, de-central separated transport and treatment of black water and grey water + stormwater. Kitchen waste co-digestion
System nr		4A	4A	5A	9A
Households	Number	30,435	2,000	30,435	2,000
Gross TACH[171]	USD/hh.yr	648	841	717	1,058
TABH	USD/hh.yr	0	0	4[172]	23[173]
TACH	USD/hh.yr	648	841	713	1,035

The estimations based on Wiegant's work show the effect of economies of scale of wastewater treatment which has been demonstrated before in section 7.7: small-scale systems are more expensive than larger-scale systems (table 7.23). Here, the TACH value of a system of 2,000 households (841 USD/hh.yr) is 30% higher than that of a system of 30,435 households (648 USD/hh.yr). The difference is relatively small, due to the fact that in-house costs and transport costs for the two system options are equal.

For the estimation of the costs and benefits of the system with urine-diverting flush toilets (system option 5A) 65% recovery of urine has been assumed. The collected urine is treated by means of struvite and CANON reactors for P recovery and N removal respectively. The brown and grey water are treated in an aerobic treatment unit. At a scale of 70,000 PE (30,435 households) the net costs of a system with urine-diverting flush toilets and separate treatment of urine (TACH = 713 USD/hh.yr) are about 10% higher than sanitation based on the use conventional cistern-flush toilets and aerobic sewage treatment (TACH = 648 USD/hh.yr). Here, the saving of drinking water due to lower flush water volumes in urine-diverting flush toilets is estimated 28 litres/cap.d or 64 litres/hh.d which corresponds to a saving of 35 USD/hh.yr[174]. This saving has been subtracted from the running costs of in-house installations in table 7.22.

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[171] Table 7.22.
[172] Yield of struvite: 105 tons struvite per year by 30,435 households.
[173] 216 kg/household per year of kitchen waste does not have to be transported by truck and composted (105 USD/ton).
[174] Drinking-water price: 1.5 USD/m^3.

In the model by Wiegant the concentrated black water collected by means of vacuum toilets (system option 9A) is treated by UASB reactor with biogas recovery followed by iron-salt dosage and an OLAND reactor for P and N removal (see chapter 6). Grey water is treated by an UASB reactor with biogas recovery followed by an aerobic membrane bioreactor. The costs of the system with vacuum toilets are about 23% higher (1,035 USD/hh.yr) than those of the system with a small-scale conventional aerobic plant (841 USD/hh.yr) and 60% more expensive than conventional drainage and sewerage at a scale of 70,000 P.E. The higher price is due to increased construction costs of transport and treatment of black and grey water. The saving of drinking water associated with lower flush water volumes in vacuum toilets are estimated at 30 litres/cap.d corresponding to 34 USD/hh.yr, and the reduction of costs for collection and treatment of kitchen biowastes at 23 USD/hh.yr. The value of energy from biogas utilization is estimated at 12 USD/hh.yr[175], while the energy saved by using UASB treatment is also 12 USD/hh.yr. The total recurrent benefits of the decentralized vacuum toilet system are estimated at about 80 USD/hh.yr[176].

A comparison of tables 7.21 and 7.23 shows that TACH values of small-scale systems by Oldenburg (2,040 households) and Wiegant (2,000 households) are in the same order of magnitude. The costs of a conventional gravity system with regular flush toilets are 872 USD/hh.yr (Oldenburg) and 841 USD/hh.yr (Wiegant) respectively. The systems with urine-diverting flush toilets from the two tables can not be compared well since the scale is much different. However, it can be concluded that systems with urine separation are hardly more expensive than conventional systems. For example in table 7.23 the TACH values of urine-diverting system and a conventional system at 70,000 P.E. are 713 and 648 USD/hh.yr. For systems with vacuum toilets the TACH values are 895 USD/hh.yr (Oldenburg) and 1,035 USD/hh.yr (Wiegant). It should be noted that the transport systems of the compared options are different: in the work of Oldenburg stormwater handling is left out of the equation, while in the estimations based on the Royal Haskoning report combined sewerage has been assumed in all system options. In view of the different assumptions in the two estimates and uncertainties related to innovative sanitation systems the encountered differences are not surprising.

The recurrent benefits in financial terms associated with reuse-oriented sanitation systems, due to savings of water, energy and costs of conventional biowaste handling and production of reusable products (biogas, compost and urine), are relatively small. In the case of system option 9A (vacuum toilets and separate handling of black and grey water) the value of recurrent benefits in comparison with a conventional system accounts for about 8.0%[177] of the total annual costs of the system. If the extra costs to make these benefits possible are estimated at 350 USD/hh/yr[178], net gains of 80 USD/hh.yr correspond to about 23% of the extra costs. The revenues of direct utilization of urine in system option 7A under present price conditions of chemical fertilizers amount to not more than about 0.3% of the annual costs[179].

[175] Estimated biogas generation rate is 130 kWh/hh.yr at a price of 0.095 USD/kWh.
[176] The recurrent benefits associated with the use of vacuum toilets are saving of flush water (34 USD/hh.yr), avoided costs of kitchen waste handling (23 USD/hh.yr), reduced energy consumption and biogas production (24 USD/hh.yr). The financial benefits of struvite production are negligible (Wiegant, 2007, p 21).
[177] Total financial benefit in terms of savings and recovery: 81 USD/hh.yr on a TACH of 1,035 USD/hh.yr.
[178] The extra TACH is 1,000 – 650 = 350 USD/hh.yr.
[179] Market value of urine as fertilizer is estimated at 2.6 USD/hh.yr. The TACH is 856 USD/hh.yr (table 7.21).

It should be noted that EU regulations do not allow direct reuse of urine and composted sludge from sewage treatment plants on land as adopted by Oldenburg and co-authors. The systems assessed in the Royal Haskoning report do not rely on direct reuse and consequently have higher treatment costs.

So far, the costs of reuse-oriented system options of group 5, 7, 9, 11 and 12 have been discussed. System groups 8 and 10 consist of systems that apply urine-diverting dry toilets in an urban setting. Faecal matter is transported by cartage and reused, and grey water and stormwater are collected in a sewer system. The crucial factor in these systems are the costs and revenues of cartage and reuse, which increase strongly with transport distance. Where urine and faecal matter could be applied to agriculture inside or close to the served community, these system options could probably be cheaper than conventional combined or separate sewerage with sewage treatment. To the author's knowledge the systems of group 8 and 10 which combine urine-diverting dry toilets with piped transport of unwanted water are as yet not used in practice.

7.9.4 Conclusions of the system-cost ranking

The sanitation and drainage systems reviewed in this thesis can be classified in four cost classes of increasing total net annual cost per household.

1. Household on-site sanitation using dry toilets (system groups 1, 2);
2. Household on-site sanitation using flush toilets, septic tanks and soakage pits (system group 3);
3. Communal one-pipe, two-pipe and three-pipe off-site treatment systems serving multiple-tap households with cistern-flush and pour-flush toilets, urine-diverting flush toilets, and urine-diverting dry toilets (system group 4, 5, 6, 7, 8, 10);
4. Small-community (decentralized) conventional and reuse-oriented systems with two until four separated waste streams (system group 9, 11, 12).

In developing countries the basic on-site dry toilet systems in the first class cost in the range of 10 to 70 USD/hh.yr. The costs of urine-diverting dry toilets (system group 2: -11 to 28 USD/hh.yr) are lower than the costs of the ventilated improved pit latrine and the dry accumulating anaerobic digester by virtue of the benefits of utilization of urine and faecal matter ascribed to the first system (table 7.2).
The costs of household on-site systems with flush toilets and disposal of wastewater to soil depend much on toilet type, water consumption and the type of wastewater treatment. In developing countries their costs are in the same range as the dry toilets or slightly higher. The third class unites a multitude of off-site options. The costs of a sewerage and wastewater-treatment system in Vietnam were estimated at about 250 USD/hh.yr. Generally stated, systems are more expensive as the number of pipes (source-separated waste-streams) increases, and improved systems with extra storage capacity in the sewer system and integration of stormwater treatment are more expensive than plain and settled systems.
Reuse-oriented systems with urine-diverting flush toilets (system groups 5 (two pipes) and 7 (three pipes)) are a little more expensive than conventional off-site systems due to slightly higher in-house and transport costs. The four-pipe systems with urine-diverting flush toilets of system group 12 are again more expensive than the two and three-pipe systems due to

additional costs of the separated treatment of brown water. Systems with vacuum toilets (system groups 9 and 11) are as yet considerably more expensive than comparable conventional systems, mainly due to the small-scale (2,000 households) at which these systems are modeled. The three system groups 9, 11 and 12 are probably applicable at a relatively small scale only and are therefore grouped in the most expensive class.

As the discussion of the work of Oldenburg and co-authors (2007) and Wiegant (2007) shows, the total annual costs per household of reuse-oriented system options depend much on the quality requirements of end products and other local conditions. The treatment of urine and black-water sludge is more expensive if these products can not be reused on land after a simple treatment. The presented estimations show that reuse-oriented systems are more expensive than conventional systems, in particular since they are experimental and laid out at a small scale. In The Netherlands the costs of a system with vacuum toilets and separation of concentrated black and grey water (system group 9) are in the order of 1,000 USD/hh.yr, while the costs of a conventional system with regular flush toilets, combined sewers and aerobic tertiary wastewater treatment (system group 4) are estimated at about 650 USD/hh.yr (table 7.23).

The system groups 8 and 10 have urine-diverting dry toilets and combined or separate sewered transport of grey and stormwater. The exploitation costs of these systems will be dependent to a high degree of the way urine and faecal matter collection and utilization are integrated into the local solid-waste management system. As until now little experience with these systems exists, no attempt at detailed cost estimation has been made.

Under present market conditions the financial benefits associated with avoided costs of drinking water, energy and kitchen-waste treatment and revenues from the production of fertilizers, soil conditioners and energy are relatively small in comparison with the total costs of systems, and also still much lower than the extra costs incurred to deliver these benefits.

Changed legal regulations, increased prices of water, energy and nutrients, larger project sizes and rewards for avoided CO_2 emissions might help to tip the balance in favour of reuse-oriented systems. This chapter also shows that costs of all systems depend largely on local conditions and that there are often significant opportunities of cost reduction by smart design, choice of materials and equipment, and community participation in infrastructure construction and operation.

Appendix of chapter 7

Table A.7.1 Costs of primary sewage-treatment technologies as compared to the reference activated-sludge technology (Capacities ≤ 500 m^3/d). Assumptions: CRF = 0.08; wastewater generation per household: 0.6 m^3/d; land costs: 10 USD/m^2.

PRIMARY TREATMENT TECHNOLOGIES CAPACITY: ≤ 500 m^3/d	Country/ Region	Horizontal - flow septic tank	Imhoff tank	Primary sedimentation + activated sludge + sludge treatment
Technology number (table 7.16)		1	2	19 Reference
Typical BOD_5 –removal efficiency (%)		20-50	20 - 40	90 - 95
Typical effluent quality (BOD_5^{20} , mg/l)		210	210	20
Alexandre et al., (1997) (15 m^3/d)	France			
Construction costs (USD/hh)		887		n.a
Recurrent costs (USD/hh.yr)		2.6		n.a
TACH (USD/hh.yr)		73.6		n.a
Alexandre et al., (1997) (150 m^3/d)	France			
Construction costs (USD/hh)			351	n.a
Recurrent costs (USD/hh.yr)			11	n.a
TACH (USD/hh.yr)			39	n.a
Guerrero-Erazo (2003) (108 m^3/d)	Colombia			
Construction costs (USD/hh)				374
Recurrent costs (USD/hh.yr)				22
TACH (USD/hh.yr)				52
Loetscher (1999) (500 m^3/d)	USA			
Construction costs (USD/hh)		134	276	1,159
Recurrent costs (USD/hh.yr)		12.1	26	69
TACH (USD/hh.yr)		22.9	48	162

Table A.7.2 Costs of primary sewage-treatment technologies as compared to the reference activated-sludge technology (Capacities > 500 m^3/d). Assumptions: wastewater generation per household: 0.6 m^3/d; CRF = 0.08; land costs: 10 USD/m^2.

PRIMARY TREATMENT TECHNOLOGIES CAPACITY: > 500 m^3/d	Country/ Region	Sedimentation tank + Anaerobic digester	Chemically enhanced sedimentation + anaerobic digester	Anaerobic pond	UASB reactor + Sludge drying beds	Primary sedimentation + Activated sludge + Sludge treatment
Technology number (table 7.16)		3	4	5	6	19
Typical BOD_5 –removal efficiency (%)		25 – 35	70	40 – 60	70 - 80	90 - 95
Typical effluent quality (BOD_5^{20} , mg/l)		210	100	150	75	20
Hydromantis (2000) (8,000 m3/d)	USA					
Construction costs (USD/hh)		553				825
Recurrent costs (USD/hh.yr)		12.4				37.6
TACH (USD/hh.yr)		56.6				104
Loetscher (1999) (8,000 m^3/d)	USA					
Construction costs (USD/hh)		88[180]				353
Recurrent costs (USD/hh.yr)		7				22
TACH (USD/hh.yr)		14				50
Oomen & Schellinkhout (1993) (8,000 m3/d)	Dev. Countries					
Construction costs (USD/hh)[181]		62		28	73.5	159
Recurrent costs (USD/hh.yr)		6		4	4.6	15
TACH (USD/hh.yr)		11		6	10.5	28

[180] Sludge digesters and drying beds not included.
[181] Land costs: 25 USD/m^2.

Table A.7.2 (continued) Costs of primary sewage-treatment technologies as compared to the activated-sludge technology (Capacities ≥ 500 m^3/d). Assumptions: CRF = 0.08; wastewater generation per household: 0.6 m^3/d; land costs: 10 USD/m^2.

PRIMARY TREATMENT TECHNOLOGIES CAPACITY: > 500 m^3/d (Continued)	Country/ Region	Sedimentation tank + anaerobic digester	Chemically enhanced sedimentation + anaerobic digester	Anaerobic pond	UASB reactor + Sludge drying beds	Primary sedimentation + Activated sludge + Sludge treatment
Technology number (table 7.16)		3	4	5	6	Reference
Typical BOD_5 –removal efficiency (%)		25 – 35	70	40 – 60	70 - 80	90 - 95
Typical effluent quality (BOD_5^{20} , mg/l)		210	100	150	75	20
Qasim (1999). (Capacity: 8,000 m^3/d)	USA					
Construction costs (USD/hh)		171				481
Recurrent costs (USD/hh.yr)		8.8				25.5
TACH (USD/hh.yr)		22.5				64.0
Somlyódi and Shanahan (1998) (8,000 m3/d)	Eastern-Europe					
Construction costs (USD/hh)		253	253			340
Recurrent costs (USD/hh.yr)		15.3	23.1			25.0
TACH (USD/hh.yr)		35.5	43.4			52.1
STOWA (1998) (19,500 m3/d)	Netherlands					
Construction costs (USD/hh)		48.6				153
Recurrent costs (USD/hh.yr)		19.0				32.4
TACH (USD/hh.yr)		22.8				44.6

Table A.7.3 Costs of primary plus secondary wastewater treatment technologies (Capacities < 500 m^3/d). Assumptions: CRF = 0.08; wastewater generation per household: 0.6 m^3/d; land costs: 10 USD/m^2.

PRIMARY PLUS SECONDARY TREATMENT CAPACITY: ≤ 500 m^3/d	Country/region	Anaerobic +Faculative ponds	Imhoff tank + Slow-rate Infiltration	Imhoff tank + VF planted filter	Imhoff tank + Trickling filter	Imhoff tank+ Trickling filter + Surface flow wetland	Imhoff + RBC	UASB + Clarifier	Oxydation ditch F/M ratio= 0.1 g BOD/g VSS/d	Activated sludge F/M = 0.5 g/g/d
Technology nr (table 7.16)		7	9	10	11	12	13	14	18	19
Typical BOD_5 removal efficiency (%)		85-90	90-98	90-95	85-90	90-95	85-90	75-80	90-95	90-95
Typical effluent quality (BOD_5^{20} , mg/l)		35	10	20	35	20	35	60	20	20
Reference										
Alexandre et al., (1997) (150 m^3/d)	France									
Construction costs (USD/hh)		566	902		861		1051		1,102	
Recurrent costs (USD/hh.yr)		21.8	29.2		33.5		33.1		41.7	
TACH (USD/hh.yr)		67.0	101		102		117		130	
Guerrero Erazo (2003) (100 m^3/d)	Colombia									
Construction costs (USD/hh)		385		417		306		167	552	374
Recurrent costs (USD/hh.yr)		14.8		13.2		14.8		14.2	24.3	22
TACH (USD/hh.yr)		45.6		46.6		39.2		27.5	68.5	52
Loetscher (1999) (500 m^3/d)[182]	USA									
Construction costs (USD/hh)		565								1159
Recurrent costs (USD/hh.yr)		9.2								69.0
TACH (USD/hh.yr)		54.4								162

[182] Land costs: 10 USD/m^2

Table A.7.4 Costs of primary plus secondary wastewater-treatment technologies (Capacities > 500 m^3/d). Assumptions: CRF = 0.08; wastewater generation per household: 0.6 m^3/d; land costs: 10 USD/m^2.

PRIMARY + SECONDARY TREATMENT CAPACITY: > 500 m^3/d	Country/region	Anaerobic +Faculative ponds	Anaerobic + Facultative + Maturation ponds	UASB + Sludge Drying Beds	UASB + Facultative Pond	UASB+ Trickling filter	Sedimentation + Trickling filter	Oxydation ditch F/M ratio= 0.065 g/g/d	Activated sludge F/M = 0.5 g/g/d	Activated sludge + N/P removal
Technology number (table 7.16)		7	8	6	15	16	17	18	19	20
Typical BOD_5 removal efficiency (%)		85-90	85-90	70-80	85-90	90-95	85-90	90-95	90-95	90-95
Typical effluent quality (BOD_5[20], mg/l)		35	20	65	35	20	35	20	20	10
Reference										
Arthur (1983) (30,000 m^3/d)	Jemen									
Construction costs (USD/hh)[183]			114				155	96		
Recurrent costs (USD/hh.yr)			1.0				4.0	7.0		
TACH (USD/hh.yr)			10.1				16.4	14.7		
Loetscher (1999) (8,000 m^3/d)	USA									
Construction costs (USD/hh)		352							345	
Recurrent costs (USD/hh.yr)		4.3							20.4	
TACH (USD/hh.yr)		32.5							48.0	
Oomen & Schellinkhout (1993) (8,000 m^3/d)	Dev C									
Construction costs (USD/hh)[184]		177		73.5	130	144		130	159	
Recurrent costs (USD/hh.yr)		4.8		4.6	5.1	7.6		16.6	15.0	
TACH (USD/hh.yr)		19.0		10.5	15.5	19.2		27.0	27.7	

[183] Land costs: 5 USD/m^2
[184] Land costs: 25 USD/m^2

Table A.7.4 (continued) Costs of primary plus secondary wastewater-treatment technologies (Capacities > 500 m^3/d). Assumptions: CRF = 0.08; wastewater generation per household: 0.6 m^3/d; land costs: 10 USD/m^2.

PRIMARY + SECONDARY TREATMENT CAPACITY: > 500 m^3/d	Country/region	Anaerobic +Faculative ponds	Anaerobic + Facultative + Maturation ponds	UASB + Sludge Drying Beds	UASB + Facultative Pond	UASB+ Trickling filter	Oxydation ditch F/M ratio= 0.065 g/g/d	Activated sludge F/M = 0.5 g/g/d	Activated sludge + N/P removal
Technology number (table 7.16)		7	8	6	15	16	18	19	20
Typical BOD_5 removal efficiency (%)		85-90	85-90	70-80	85-90	90-95	90-95	90-95	90-95
Typical effluent quality (BOD_5^{20} , mg/l)		35	25	65	35	15	20	20	10
Reference									
Hydromantis (2000) (8,000 m^3/d)	Canada								
Construction costs (USD/hh)							568	825	908
Recurrent costs (USD/hh.yr)							23.1	37.6	47.9
TACH (USD/hh.yr)							68.5	104	120
STOWA (1998) (19,500 m^3/d)	NL								
Construction costs (USD/hh)								152	276
Recurrent costs (USD/hh.yr)								32.4	41.0
TACH (USD/hh.yr)								44.6	63.1
Somlyódi and Shanahan (1998) (8,000 m3/d)	Europe								
Construction costs (USD/hh)								339	625
Recurrent costs (USD/hh.yr)								25.0	41.0
TACH (USD/hh.yr)								52.1	90.8

CHAPTER 8 DRAINAGE AND SANITATION IN HO CHI MINH CITY, VIETNAM A DIAGNOSTIC STUDY

8.1 Introduction

On approach of Ho Chi Minh City by airplane a visitor may be struck by vast arrays of new industrial zones and colourful urbanization amidst innumerable patches of glistening water surfaces. On the road he will be stunned by the frantic activity of its population, its traffic, the gaiety at night. Soon he will run into a traffic jam in a flooded street and notice the ubiquitous acrid smell of the black water in the canals. If he is an environmentalist interested in sanitation and drainage many questions come to his mind. How this city manages its stormwater and wastewater? What is the impact on the Dong Nai - Saigon River system and on valuable coastal ecosystems, such as the mangrove areas near the sea? How all this is managed? What technologies could be applied as solution of the problems in the different areas of the city?

This chapter is an attempt to identify and analyze the problems of urban water management with an emphasis on drainage and sanitation. It consists of three parts. First an introduction is given of Ho Chi Minh City's development, the elements of the urban water chain and their critical issues, the institutions related to environmental infrastructure and ongoing urban upgrading projects (sections 8.2, 8.3 and 8.4). Then, the consequences of deficient sanitation and drainage in unplanned neighborhoods are analyzed in 8.5, while in 8.6 the lessons learnt in the Tan Hoa – Lo Gom urban upgrading project are summarized and assessed. Finally, this multi-level study is completed by a strengths - weaknesses analysis of the reigning drainage and sanitation management practice (8.7) and the outlines of long-term action plans in four sectors closely connected to the problems of drainage and sanitation (8.8).
The analysis in this chapter shows, that sustainable drainage and sanitation solutions are not obvious: for some situations several options could be feasible, for others none seem adequate. This was the reason to develop in chapters 3 to 7 the SANCHIS multi-criteria decision making tool that allows experts and stakeholders to make a rational choice out of a wide range of well-known and innovative drainage and sanitation options. Once developed the tool was used to find adequate drainage and sanitation systems for Ho Chi Minh City (chapter 10 and 11) and subsequently improved on the basis of the gained experiences. The tool can fulfill a useful function in making future drainage and sanitation action plans in cities in Vietnam and other developing countries.

The description of the Ho Chi Minh City case is based on information gathered by means of interviews, field observations, stakeholders workshops and professional and scientific literature during a period of more than 10 years (1999 – 2009). Three MSc thesis studies by students of Wageningen University have greatly contributed to a better insight in the problem of drainage and sanitation in the city (Gordillo Manzano, 2004; Stamper, 2004; Kragic et al., 2005).

8.2 The urbanization in Metropolitan Ho Chi Minh City

8.2.1 Growth of population and urbanization rate

Ho Chi Minh City is Vietnam's largest city and most important economic center. Although the city's industrialization had already gained momentum in the 1960s, its present growth took off after the nation embarked on its *doi moi* (renovation or economic reform) policy in the late 1980s. In 2007 the city contributed by 30% to the country's industrial output and by about 22% to the national GDP of 70 billion USD (Du, 2007) and World Fact Book[185]). During most years of the past decade its GDP growth amounted to over 11% (Thanh, 2007). Since this thesis analyses the relationship between sanitation development and rapid urbanization, the latter is first depicted by surveying the population growth and housing development in urbanizing districts. The location and a few characteristics of the districts are summarized in figure 8.1 and table 8.1. The numbers and names in figure 8.1 correspond to their counterparts in table 8.1.

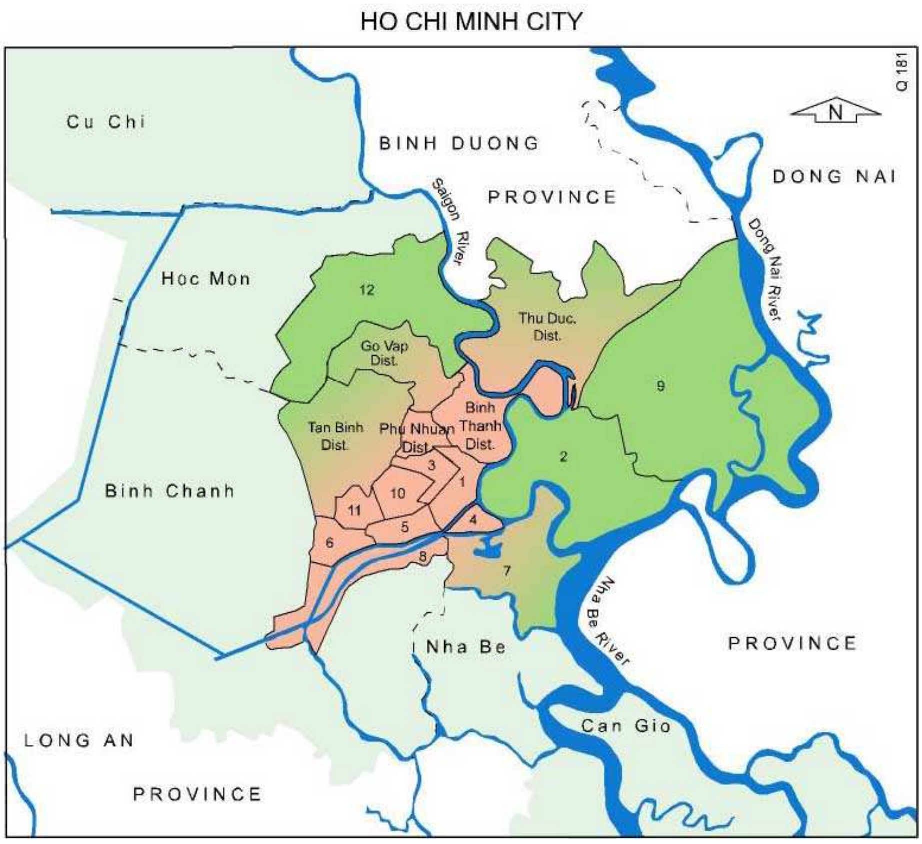

Figure 8.1. Administrative district map of Ho Chi Minh City.

Metropolitan Ho Chi Minh City, which includes the inner city and vast rural and urbanizing surroundings, covers 2,094 km^2, administratively divided into 18 urban and 6 rural districts. According to the Master Plan of 1998 the present inner-city area of 140 km^2 will expand to 650 km^2 by 2020 (Stamper, 2004), which corresponds to an annual urban growth of 7%.

[185] https://www.cia.gov/library/publications/the-world-factbook/geos/vm.html (accessed last on November 6, 2008).

Table 8.1 Population and population change in the administrative districts of Ho Chi Minh City Province (Source: Statistical Office Ho Chi Minh City, several years).

District (1)	Official designation (2)	Status (3)	Area (km^2) (4)	Population (yr 2009) (5)	Population density (yr 2009) (inhab/km2) (6)	Population change 2009 - 1997 (inhab) (7)
Inner City						
1	Urban	Urban	7.7	178,878	23,141	-103,185
3	Urban	Urban	4.9	189,764	38,570	-70,654
4	Urban	Urban	4.0	179,640	44,910	-41,010
5	Urban	Urban	4.1	170,462	41,576	-80,925
6	Urban	Urban	7.0	251,912	35,987	-28,424
8	Urban	Urban	18.8	404,976	21,541	57,886
10	Urban	Urban	5.7	227,226	39,864	-44,376
11	Urban	Urban	5.0	226,620	45,324	-33,539
Phu Nhuan	Urban	Urban	4.9	174,497	35,758	-27,957
Binh Thanh	Urban	Urbanizing	20.8	451,526	21,708	33,787
Go Vap	Urban	Urbanizing	19.2	515,954	26,873	280,998
Tan Binh[186]	Urban/rural	Urbanizing	38.5	810,431	21,050	298,246
Outskirts						
2	Urban	Urbanizing	50.2	145,981	2,920	50,762
7	Urban	Urbanizing	35.7	242,284	6,787	143,904
9	Urban	Urbanizing	114.0	255,036	2,237	135,590
12	Urban	Urbanizing	52.8	401,894	7,612	274,435
Thu Duc	Urban	Urbanizing	47.8	442,110	9,251	271,045
Hoc Mon	Rural	Urbanizing	109.2	348,840	3,195	162,969
Binh Chanh[2]	Rural/Urban	Urbanizing	304.6	994,792	3,281	730,909
Nha Be	Rural	Rural	100.4	99,172	988	36,131
Can Gio	Rural	Rural	704.2	68,213	97	11,040
Cu Chi	Rural	Rural	434.5	343,132	790	76,106
Total HCMC				7,123,340		

In the period 1997-2009 the population of Metropolitan Ho Chi Minh City has grown from 5.0 to 7,1 million (table 8.1). The City's Master Plan recommends a restriction of the population in the inner city districts from the present 3.8 million to 3 million people and a gradual replacement of the surplus population to new urban satellite cities (e.g. Bien Hoa and Long An) and resettlement zones (Camp Dresser McKee International, 2000).

The growth of the population and the economy engenders an enormous expansion of industrial settlements, infrastructure and housing. As per table 8.1 (column 7) the population increases at a high rate in the peri-urban districts Go Vap, Tan Binh, 7, 9, 12, Thu Duc, Hoc Mon and parts of Binh Chanh. These districts recently were and partly still are agricultural areas in a rapid process of transformation. In 12 years time (1997-2009) the population of

[186] In 2004 Tan Binh district has been divided into the districts Tan Binh and Tan Phu and district Binh Chanh into Binh Chanh (rural) and Binh Tan (urban).

these 8 districts grew by more than 2.1 million people. At the same time the density in most central districts diminishes through relocation projects, increased commercial activities and building of up-market apartments. Around the year 2000 the city's growth has accelerated and increases since then by about 200,000 persons annually. Assuming 5 persons per household this would imply a housing construction demand of 40,000 houses annually. Through a backlog in housing studies the number of houses built is unknown.

The low population growth in district 2 (about 50,000 people over the period 1997 to 2009) in comparison with other urbanizing districts of the city needs an explanation. Although located next to the core district 1, it was until recently considered as a muddy flood plain unfit for building. However, at the end of the 1990s it has been destined to become the place for high-level services, institutions and residences and a new bridge (realized in 2008) and tunnel (to be opened in 2010) will enhance the communications between district 2 and the center of the city. Consequently, this district falls under a regime of strict urban planning with little opportunity for the spontaneous building found in other districts. It may be concluded that up to now housing development in Ho Chi Minh City under a formal regime of planning and building is very slow.

8.2.2 The nature of urbanization

The present problems of infrastructure in Ho Chi Minh City are not only associated with the rapid growth, but also with the - related - unplanned nature of housing development in the near past. During the Vietnam war which ended in 1975 Saigon's population (Ho Chi Minh City) grew rapidly, due to massive migration from the dangerous countryside. In this time large squatter areas emerged, in particular along the banks of the city's canals. After the country's reunification in 1975 anti-migratory regulations were put in place and housing and infrastructure development became state-directed. However, due to the post-war disarray, in particular at the institutional level, and general poverty housing and infrastructure development stagnated until the end of the 1980s. After the introduction of the market-oriented reform (doi moi) since 1986, a combination of factors, among which improving incomes, opening up to foreign investment and western lifestyles, and new policies on land and housing, inspired households and private enterprises to an explosion of private construction activities (Evertsz, 2000; Luan and Vinh, 2001). Very often these activities trespassed against reigning land-use and housing regulations. According to expert estimates 70 – 80% of the housing in Hanoi and Ho Chi Minh City were constructed under a popular or spontaneous regime (Duc Nhan, 2001), Nguyen Quang Vinh, 2005[187]). This popular building occurred without spatial, architectural and infrastructure plans, as such plans did not exist or could not be enforced at the time. Unplanned neighborhoods can be characterized by very high building and population densities (up to 1500 inhabitants per hectare), extremely narrow roads, lack of green spaces and serious problems with water supply, drainage and sanitation infrastructure. Their inhabitants are not necessarily poor as popular building was practiced by all strata of society.
At the background of unplanned housing and infrastructure development are land management and planning institutions that are not able to cope with the task at hand. The sheer size of this task may be put in a proper perspective, if one realizes that in housing alone Ho Chi Minh City's authorities have to regulate the establishment of about 40,000 houses

[187] Interview author with Nguyen Quang Vinh in 2005.

annually, while The Netherlands as a whole with all its developed institutions has a housing target of 80,000 units annually, and is not able to achieve this[188].

Though according to the Housing Law of Vietnam housing development should be guided by approved plans, the informal building outpaces the formal decision-making process about these plans and/or their enforcement. City planners in Vietnam speak in this context of 'suspended planning' (Luan, 2001, p.27; Stamper, 2004) characterized the stakeholders involved in housing as an 'orchestra without a conductor'. According to (Stamper, 2004, p 30) suspended planning is caused by inadequacies of:

- Predictions by the Urban Planning Institute about future population settlement;
- Synchronization between institutional stakeholders;
- Budget for plan development, especially at district level;
- Support to the implementation of plans.

Departments involved in infrastructure development, like UPI, DT, DONRE (appendix 8.1) and the districts may have different priorities and overlapping tasks, and they often appear unable to coordinate their activities in a certain district. Authorities of rural communes and districts, increasingly facing land needs of urban projects, lose control as city authorities take over the development. The confused administrative situation weakens authorities' grip on the spatial development (Van den Berg et al., 2003). Since the end of the 1990s gradually, however, the state authorities, collaborating with international donors (World Bank, Asian Development Bank and many others) and large investment companies, are successfully trying to regain their grip on the urban development. The modern spacious housing areas in Saigon South (Waibel, 2006) and large urban upgrading projects testify of this process. New laws and policies are put in place to provide a regulatory framework to end uncontrolled urban spread. An example is the new Housing Law of 2005 (Ministry of Construction, 2005). Due to residual institutional weaknesses, particularly at district level, regulations may not (yet) be well implemented, so that unplanned building has not stopped by 2008[189].

8.2.3 Conclusions on population growth and urbanization

Ho Chi Minh City's population has grown from 5.0 to 7.1 million in the period 1997 to 2009, while the population of Vietnam as a whole had reached the number of 84.1 million by that time (GSO, 2008[190]). Since the year 2000 the city's population growth is linear with 200,000 new citizens annually, which creates an estimated housing demand of about 40,000 new family houses per year. The expansion of the built up area has predominantly taken place in the peri-urban districts Go Vap, Tan Binh, Thu Duc, district 12, Hoc Mon and Binh Chanh (figure 8.1). Much of the housing construction in these areas has taken place under a regime of deficient planning with serious consequences to the quality of the infrastructure. Where building is under the control of planning, such as in district 2 and 7, the growth of housing has shown to be relatively small and destined to the upper strata of society. The backlog is caused by inadequate land-management and planning systems that are not able to cope with their responsibilities. In addition, housing policies in Vietnam do not seem to focus on building for the low and middle-income groups, but rather leave housing development to market forces,

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[188] http://cbs.statline.nl.
[189] Interviews with experts of the Urban Planning Institute (UPI) and the Department of Construction (DOC).
[190] General Statistics Office of Vietnam (www.gso.gov.vn)

which implies that land prices have skyrocketed and that most new planned housing is unaffordable to the majority of house seekers. The consequences of population growth and urbanization for the water infrastructure are investigated below.

8.3 Water and sanitation in Ho Chi Minh City: infrastructure and critical issues

Applying a flow-based approach this section describes the water infrastructure in Ho Chi Minh City and identifies its critical issues. The subsections below discuss consecutively water resources (8.3.1), water supply (8.3.2), stormwater and high tide (8.3.3), municipal sewage (8.3.4), industrial wastewater (8.3.5), the impact of the city on the Saigon and Nha Be rivers (8.3.6), domestic sanitation and drainage (8.3.7), wastewater treatment (8.3.8) and wastewater reuse (8.3.9). The main challenges posed by the city's water infrastructure are summarized in subsection 8.3.10.

8.3.1 Water resources

The main water resources of Ho Chi Minh City are the surface water adducted by the Saigon and Dong Nai rivers, groundwater and rainwater. The annual rainfall in the region of Ho Chi Minh City is about 1,800 mm of which most falls in the rainy season between April and October (Statistical Office HCMC, 2007). The quantity of natural renewable water resources for the country as a whole is estimated at 11,109 m^3/capita/yr (2002)[191]. The rivers Dong Nai and Saigon are 'tamed' rivers as their flow is regulated by respectively the Tri An and Dau Tieng reservoirs in the upstream regions. The average flow of the Dong Nai river in the dry season is 210 m^3/s (18.1 mln m^3/d) and the Saigon River is fed by 7 m^3/s (600,000 m^3/d) which is judged as sufficient for the intake of the drinking-water supply plant at Tan Hiep (People's Committee of Ho Chi Minh City, 2002). Although the overall available water quantities in the wider region of the city may be considered as plentiful, Ho Chi Minh City may expect serious water quality and groundwater scarcity problems, unless adequate measures are taken (Phu, 2007). These problems are sketched in the following subsections.

8.3.2 Water supply infrastructure

The domestic and industrial water supply of the city is based on surface and groundwater. The main supply stations, their sources, capacities and problems are listed in table 8.2. According to this table the total amount of supplied surface water and groundwater was about 1.65 million m^3/d in 2006. The actual groundwater extraction is not exactly known and was believed to be about 520,000 m^3/d in the beginning of the 2000s (People's Committee of Ho Chi Minh City, 2002) and about 600,000 m^3/d in 2008 (ICEM, 2009b, table 11.2).

Due to fast urbanization and industrialization, water demand will continue to grow rapidly and supply was expected to reach a capacity of 2 million m^3/d by 2010 (PC HCMC, 2002). Presently, the drinking water is distributed over the categories as follows. 79% of the water is used in households, 11% in industries and 10% in commercial establishments. Approximately 87% of city's population is considered adequately served (June 2007), among whom 11% living in rural areas obtains water from shallow wells. In some areas without a piped network water vendors are active. From the users' side the most important complaints regarding the water provision are discontinuous supply and deficient water quality. The production of drinking water from surface water is not expected to meet quantitative problems in the

[191] earthtrends.wri.org/pdf_library/country_profiles/wat_cou_704.pdf

coming decade as the flow-rates of Saigon and especially Dong Nai Rivers are amply sufficient. Both rivers are, however, increasingly affected by pollution, so that it is becoming increasingly difficult to produce drinking water at low cost with a good quality. In the Thu Duc and Binh An plants the main problem is a high concentration of algae in the intake water during the dry season. The Tan Hiep water on the other hand is affected by salt intrusion into the Saigon River. Salt intrusion is expected to increase significantly, as the level of the East Sea rises due to global warming, and will therefore be a growing and important concern in the future (ICEM, 2009b, section 12.2).

Table 8.2 Sources of drinking-water supply in Ho Chi Minh City (2007).

Source	Treatment Plant	Capacity (m^3/d)	Problems
Dong Nai River	Thu Duc	750,000	Algae in dry season
Dong Nai River	Binh An	100,000	High concentration of particles
Saigon River	Tan Hiep	300,000	Salinity in dry season
Groundwater	A multitude of extraction points	> 500,000	High iron and manganese, falling water tables
Total capacity (2007)		> 1,650,000	

Phu (2007) points out that groundwater tables are falling rapidly (up to 5 meter in 5 years time), which demonstrates over-extraction, so that the present estimated extraction of over 500,000 m^3/d probably has to be reduced in the future. The increasing problems of surface and groundwater supply show that further increase of supply to meet the growing demand will meet very serious challenges, despite the city's location in the drainage area of two big rivers.

8.3.3 Management of stormwater and high tide

Ho Chi Minh City is built in a low-lying marshy area along the Saigon River and increasingly spreads in eastern direction over the flood plains between Saigon and Dong Nai rivers. The highest natural ground level in the central districts is about 10 meter above sea level, but several new districts (districts 2, 7, 9 and Binh Chanh) are situated in flood plains of the Dong Nai and Saigon River and the level there is often less than 1.5 m above the mean sea level (MSL) (JICA/ Pacific Consultants International, 1999b, part E p 4). In these areas flooding at high tide is a normal phenomenon. Originally the city is drained by a dense network of natural drains and constructed canals. Due to the low location and gradual increase of impervious built-up zones with simultaneous filling in of drainage canals, most districts of Ho Chi Minh City face frequent flooding now. Three types of floods are distinguished: floods caused by strong rainfall and insufficient drainage capacity, floods caused by high tide in the Saigon and Dong Nai rivers and a mixed type of floods caused by the two phenomena in conjunction. In addition, extreme floods occurring during tropical storms could be distinguished (ICEM, 2009b, section 2.2).

Based on a survey carried out in 1998 the urban flood area was estimated at 3461 ha, which was at the time about 20% of the urban built-up area affecting almost 1.18 million people (28% of the population at that time (JICA/ Pacific Consultants International, 1999b, part E. p 37). The flood depths varied from 20 to 60 cm. A later report identified 100 flooding sites in the province of which 85 in the high-density urban districts of the city (People's Committee of Ho Chi Minh City, 2008). Most affected was district 6 with 20 sites (figure 8.1). More recently, the area in Ho Chi Minh City affected by regular floods and extreme floods was estimated at 108,309 and 135,526 ha respectively (ICEM, 2009b, table 2.2).

Ho Chi Minh City drains its surplus water from 6 catchment areas via combined sewers and canals to the Saigon, Nha Be and Dong Nai rivers. The canals also play an important role in transportation. The width of the drainage canals in the central city drainage zone for example varies from about 10 m to more than 100 m (JICA/PCI, 1999, part E, table E 3.4). According to JICA-PCI (1999) the main problems related to the canals in the city are reduced drainage capacity and inadequate embankments and protecting dikes. The capacity of these canals has deteriorated, due to natural sedimentation, encroachment of poor peoples' housing on the embankments, the massive deposition of solid wastes and lack of dredging. In order to restore the drainage capacity, but more importantly for social and economic reasons, the city has embarked on large-scale relocation of those dwelling along the canal embankments, demolition of their housing, dredging of the canals and lining of embankments (8.4).

A second main cause of flooding, e.g. in Binh Chanh and district 7, given the absence of dikes and pumped drainage, is the inadequate and uneven heightening of land prior to building. The Sewerage and Drainage Master Plan of 1999 recommends heightening of land prior to building to reach a level of at least 2.0 m above MSL, which is 0.3 m above the chosen design high water level of 1.7 m above MSL (JICA/ Pacific Consultants International, 1999b, part E, p E-47). Up to 2008 this recommendation has not reached the status of a building code, though a proposal is under consideration[192]. Consequently, even very recent, planned residential areas, such as projects in Thu Thiem, district 2, have not been heightened to a level that guarantees gravity drainage and reduces the risk of flooding to an acceptable frequency. As these regulations come late for many parts of the city and are not observed well, authorities and households have to take costly measures like road and floor heightening after neighborhoods have been built in order to prevent frequent flooding. In addition, mention is made of land subsidence at a number of locations in Ho Chi Minh City, which could exacerbate flooding. However, studies on this topic have not been published (ICEM, 2009b, section 2.3). The damage to property in Ho Chi Minh City due to natural disasters (mainly flooding) over the period 1997 to 2007 was estimated at 12.6 million USD (ICEM, 2009a, section 7). Without doubt, the combination of city expansion in low areas, particularly in the Southern and Eastern districts, and sea-level rise due to global warming, which is estimated at about 20 cm in 2030 and 45 cm by 2070 (Wassmann et al., 2004), demands significantly more efforts to fight flooding in the future than are made up to now. Steps to be taken comprise a wide range of adaptive and preventive measures (ICEM, 2009a, section 8). In new low-lying building areas a choice has to be made between surrounding them with dikes and pump excess water out or considerable heightening of the land before building. Such measures have to be combined with land development the leaves open space for water retention (Cattoor and Gosseye, 2008). In 2009 the Vietnamese government has approved a project known as "the Irrigation Plan for Flood Control for the Ho Chi Minh City Area to 2025" with a proposed budget of 650 million USD. This plan includes the construction of major drainage and dyke works to enclose the city and measures to divert floods, rainwater and high tides (ICEM, 2009b, section 1.5).

[192] Personal communication: Mme Pham Thi Thanh Hai (UPI) (2008).

8.3.4 Municipal sewage

The dry weather flow of sewage in Ho Chi Minh City in 1997 was estimated at 700,000 m^3/d (Drakakis-Smith and Dixon, 1997; JICA/ Pacific Consultants International, 1999b, p F-2). It must have passed the 900,000 m^3/d in 2007, as the drinking-water flow has increased to more than 1.65 million m^3/d (this study[193]). Sewage flow is expected to rise to over 2.0 million m^3/d in 2020 (JICA/ Pacific Consultants International, 1999f, p 7-3). The BOD_5 load of this sewage is expected to increase from about 170,000 kg/day (1997) to 383,000 kg/d in 2020 (JICA/ Pacific Consultants International, 1999f, p. 7-3). In the central districts sewage is collected by means of combined sewerage (sewers primarily laid out for rainwater, but also used for wastewaters) and discharged directly to surface water. The majority of the urban houses have a septic tank for pretreatment of their wastewater, especially the water from toilets (see also subsection 8.3.7). Twenty-four samples taken from sewers at 9 different locations had COD concentrations varying between 55 and 623 mg/l with an average of 270 mg/l and BOD_5 - concentrations ranging from 35 to 497 mg/l with an average of 184 mg/l (table 8.3). The COD : N ratios of most samples lie in ranges which are typical for raw domestic sewage or septic-tank effluent[194]. In many places in Ho Chi Minh City the sewage can be characterized as having a low to a very low strength (Metcalf and Eddy Inc, 2003, p 186). This low strength is thought to be caused by groundwater infiltration into sewers and organic matter conversion in septic tanks and the sewers themselves. It is well-known that deficient sewer construction allows much infiltration where groundwater tables are high. Similar low-strength sewages were found by Jin et al.(1998) in South-Chinese cities. In the dry season, the canals in the city mainly carry sewage in addition to their natural flow. Den Canal and Nhieu-Loc Thi-Nghe Canal show qualities similar to water in sewers.

Tan Hoa- Lo Gom Canal, Tau-Hu and Doi-Te Canal show remarkably high values for COD and the COD : N ratio, which may be due to (incidental) discharges of high-strength industrial effluents and solid wastes in the local drainage basins. The scarce data, however, do not allow more detailed conclusions. The design of future sewage-treatment plants would require more precise insight into the factors that determine the quality of sewage in the city than is available at this time. Since most sewage is discharged only partially treated by means of septic tanks or not treated at all, the city copes with severe surface water-pollution problems in its canals. The degree to which Saigon River is affected is discussed below.

[193] Assumptions: water losses at distribution: 30%, and sewage return factor: 80%.

[194] According to the indicative data given in chapter 5, table 5.2, domestic sewage has a COD : N ratio of 8.0. In septic tank effluent a COD : N ratio of about 5 could be expected due to partial removal of COD.

Table 8.3 Water quality in sewers and canals in Ho Chi Minh City and of Saigon River. [1] Average of 24 samples from sewers all over the city (data sources: CEFINEA, 1999 and CENTEMA, 2002).[2] VITTEP, 12 samples in Jan-Mar 2004. [3] Sampling in main canals and Saigon River at low tide (JICA/ Pacific Consultants International, 1999f, table 2.9 and 2.10).

Water sampling location	COD mg/l	BOD_5 mg/l	N_{tot} mg/l	P_{tot} mg/l	Total Coliforms MPN/100 ml
Sewage[1]	270	184	33	5.3	$2*10^7$
Den Canal [2]	253	167	38	5.3	$24*10^7$
Nhieu Loc Thi Nghe Canal[3]	234	174	13	1.3	$1.1*10^7$
Tan Hoa-Lo Gom Canal[3]	988	536	46	2.9	$1.5*10^7$
Tau Hu/ Doi Te Canal[3]	400	251	11	0.6	$2.1*10^6$
Tham Luong Canal[3]	240	181	2	0.2	$1.5*10^7$
Saigon River at Thanh Da[3]	135	61	1.3	0.06	$1.1*10^7$

8.3.5 Industrial wastewater

Ho Chi Minh City was already one of the most industrialized places in Vietnam before its reunification in 1975 and since the end of the 1980s industrialization has soared. The number of non-household industrial enterprises has increased from 2068 in the year 2000 to 7422 in 2006 (Ho Chi Minh City Statistical Office, 2008). Since the beginning of 1990s the government directs settlement of factories to industrial parks in order to bridle negative environmental impacts. In 2008 there are in Ho Chi Minh City 13 industrial parks with a total size of about 24 km^2 of which 6 have a central wastewater-treatment plant (Waibel, 2006; Phu, 2007; People's Committee of Ho Chi Minh City, 2008). In the industrial parks without central treatment facility the individual enterprises have to pre-treat their wastewater to the level that is required for discharge to a central wastewater treatment plant. The treated and untreated effluent of industrial parks is discharged into the network of canals and river branches all through the city and its surroundings.

At the beginning of the 2000s DONRE had blacklisted more than 1,400 small- and medium-scale factories for relocation to industrial parks, based on their strong environmental impacts . The People’s Committee of Ho Chi Minh City has carried out this relocation and environmental improvement programme under the name ROPETIZ (Relocation of Polluting Enterprises to Industrial Zones).
From an evaluation of this programme in 2008 can be concluded, that about 45% (630) of the industries have moved to industrial parks, while 33% (463) have stopped, and 9% (127) changed to non-polluting activities (People's Committee of Ho Chi Minh City, 2008). The fate of the remaining percentage is unclear. From the point of view of reduction of industrial pollution in crowded residential areas the ROPETIZ programme may be called a success. It is, however, improbable that the pollution of relocated factories is properly addressed, as more than half of the industrial parks has no central wastewater-treatment plant and the performance of wastewater-treatment plants is often inadequate (Kragic et al., 2005).
The total flow of industrial wastewater in the city at the end of the 1990s was estimated at 300,000 m^3/d (Drakakis-Smith and Dixon, 1997). A prognostic for the Southern Focus Economic zone, including the Saigon, Dong Nai, Thi Vai and Soai Rap rivers, predicts a total discharge of industrial wastewater of over 1.0 million m3/d with a COD load of 107,000 kg/d by 2010 (People's Committee of Ho Chi Minh City, 2002, Ch 4-p 6/7).

8.3.6 The impact of Ho Chi Minh City on Saigon and Nha Be Rivers

Ho Chi Minh City's surface water system is determined by the Saigon and Dong Nai Rivers that both are strongly influenced by rainfall and tide. Figure 8.2 shows the BOD_5 and dissolved oxygen (DO) concentration profile of Saigon River on its course through Ho Chi Minh City. For the points 1, 2, 3 and 5 the graph is based on average values of 12 monthly samples taken in 2004. The total distance along the river between point 1 (Thu Dau Mot) and point 5 (Nha Be river) is approximately 60 km.

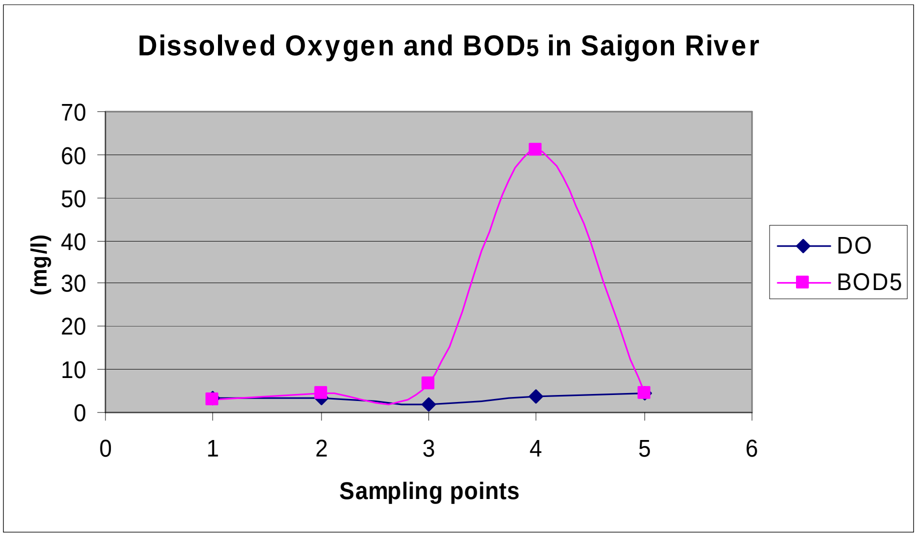

Figure 8.2 Water quality of Saigon River (Point 1: Thu Dau Mot (upstream); 2: Binh Phuoc; 3: Phu An; 4: Thanh Da; 5: Nha Be River (downstream)) (Sources: points 1, 2, 3, 5 from DONRE, 2005; Point 4 from (JICA/ Pacific Consultants International, 1999f, table 2.10).

The BOD_5-concentration amounts to values between 3 and 9 mg O_2/l before the river reaches the city. Due to the city's discharges the BOD_5-values soar to 20 – 60 mg O_2/l in the Thanh Da (point 4 in figure 9.2) to Tan Thuan stretch. Data from the river at Tan Thuan come from JICA/PCI, 1999, p 2-17 and table 2.10. After the confluence of Saigon River with the much bigger Dong Nai River (point 5: Nha Be River) the BOD_5 –concentration has decreased to about 4 mg/l. Due to bacterial oxygen consumption, the dissolved oxygen (DO) concentration in the most polluted downstream section of Saigon River closely reaches anaerobicity, which indicates serious stress to the aquatic ecosystem. The lowest measured DO-value at Phu An in 2005 was 0.3 mg/l (point 3) at a DO saturation concentration of 7.9 mg/l at 27^{o} C. As data of water quality of pristine headwaters of the Saigon River are not available, an assessment of the influence of Ho Chi Minh City on the river-water quality is made by comparing the quality downstream of the city with average values in European large rivers, Vietnamese surface-water quality requirements and European target values. These target values are concentrations that would occur if no anthropogenic influence on river would occur so that the original ecosystem is supported. It should be understood that European rivers have reached the quality indicated in table 8.4 through decades of anti-pollution measures. Comparison of the qualities of Nha Be River and EU rivers and the targets seems to suggest, that the influence of Ho Chi Minh City on the quality of the Nha Be River is modest.

Table 8.4 River water quality up- and downstream of Ho Chi Minh City, average quality of European large rivers, and Vietnamese and European target values.

Location	BOD_5 (mg/l)	DO saturation (%)	N_{tot} (mg/l)	P_{tot} (µg/l)	E. coli (MPN/100ml)
Nha Be River (downstream of Ho Chi Minh City)[195]	4.4 (0.5-11)	57 (39-78)	1.5 (0.9-2.8)	170 (78-454)	4,970 (20-25,000)
Average in European large rivers (EU-countries) (1998)[196]	2.2	97	3	195	n.a.
Vietnamese requirement (TCVN 5942-1995 A)	< 4	>76[197]	<2.2	n.a.	5,000
Target value (EU rivers)	-	100	1	5 - 50	2,000[198]

All parameters show increased values and the average DO-saturation (57%) is insufficient, but total nitrogen and total phosphorus concentrations are lower than the average of European rivers. This small influence could be explained by biological conversion processes in the drainage network, the dilution of the sewage and self-purification by the vast water masses contained in the downstream reach of the estuary. From a comparison between concentrations in Nha Be river, the Vietnamese standard and the European target values, it could be concluded, that wastewater treatment efforts should put emphasis on organic matter, pathogens and phosphorous removal, but the need of N removal seems remote. Hydro-ecological studies would have to assess the long-term effects of the city's emissions on the ecosystems in the mangrove areas and coastal zones of downstream Nha Be River (the lower part of the Dong Nai river) in Can Gio district.

8.3.7 Domestic sanitation systems and drainage

The toilets used in Ho Chi Minh City are pour-flush (PF) toilets, regular cistern flush and dual-flush cistern flush (CF) toilets. According to the Statistical Yearbook of Ho Chi Minh City (1999) 79% of the households in the city were equipped with a cistern-flush (CF) toilet system. This figure seems to suggest that CF toilets are the dominant system in the urban districts, but it is certain that many of them are manually flushed due to absence or breakdown of flushing devices, so that the water consumption for toilet flushing is probably lower than expected on the basis of the high prevalence of CF toilets.

In 1997 a survey was carried out on the sanitation systems in Ho Chi Minh City. Its results are summarized in table 8.5 (JICA/ Pacific Consultants International, 1999f, table 4.1)[199]. The total number of households in the study area at that time was approximately 600,000. It was concluded that 4 different sanitation systems are in use: the flush-toilet with septic tank, the leaching pit (also named pit latrine), the hanging-hole or fish pond toilet (= dry toilet above pond or canal) and public toilets.

195 Averages based on monthly sampling in 2004 (DONRE, 2005).
196 Data sets from European Environmental Agency: http://www.eea.europa.eu/themes/water .
197 The Vietnamese DO requirement for surface water (TCVN 5942-1995A) is 6.0 mg/l. At 27 °C this corresponds to a saturation value of 76%. See this thesis appendix A.1.
198 Dutch quality of surface water used for swimming.
199 No more recent data were collected after 1997 (Nguyen Bao Khanh, Urban Drainage Company, pers. comm., 2008).

Table 8.5 Number and percentage of households using different sanitation systems in Ho Chi Minh City (after (JICA/ Pacific Consultants International, 1999f, table 4-1).

Sanitation system	Number of households in study area	Fraction (%)
Toilet with standard septic tank	304,794	52.7
Toilet with non-standard septic tank	144,500	25.0
Leaching pit	170	0.03
Hanging-hole (fish pond) toilet	48,640	8.4
Public toilet	53,064	9.1
No facility	27,631	4.8
Total	578,799	100

According to table 8.5 75 - 80% of the houses in the city are equipped with a septic tank, but these are not always built according to the standard of the Ministry of Construction (Ministry of Construction, 1988, TCVN 4474-87). A very small number of households (170) used a pit latrine, but much more popular still was the toilet above the water (hanging-hole or fish pond toilet) used by about 50,000 households at the time. Vietnamese environmental authorities consider pit latrines and hanging-hole toilets inadequate and they are gradually phased out. A considerable percentage of the population did not have access to a private toilet and was using public toilets (9.1%) and 4.8% of the households indicated to lack access to both private and public toilets. The septic tank is either connected to a stormwater sewer, forming the settled combined sewer system, or with effluent discharge to a soakage pit or into a local pond or channel. The settled combined sewer system as depicted in figure 8.3 collects the grey water (C) and the septic-tank effluent (B) into a local wastewater sewer and then combines this wastewater with the local rainwater run-off into one sewer pipe which discharges to a local canal or a river[200].
The standard septic tank for an individual household in Vietnam is a watertight tank with two compartments and is dimensioned for the treatment of black water only. The volume is about 2 m^3 for a 6 person household. The household septic tanks play an important role in the Vietnamese urban sanitation systems, since they provide removal of organic matter in the order of 40% of the black water COD prior to discharge[201](subsection 6.3.5). In addition they protect the sewers against blockage, which is especially relevant where toilet-flushing water is not amply available and sewers are laid out in flat areas with a small slope. Based on a study carried out in Hanoi Harada and co-workers (Harada et al., 2007) conclude, however, that the management of most septic tanks is severely deficient. The fate of the septic-tank sludge is described in subsection 8.3.8.

According to the Drainage and Sewerage Master Plan (JICA/ Pacific Consultants International, 1999f, p 3-6) the combined sewers in Ho Chi Minh City had a total length of 932 km and covered an area of 65 km^2 or about 46% of the inner city districts. The districts 1, 3, 4, 5, 6, 10 and Phu Nhuan possessed a drainage pipe length of more than 100 m/ha, which means that the combined settled system is the dominant sanitation system in these areas. In other districts, especially in the wards realized under a regime of self-building piped sewers were often absent (see below) or existed in a rudimentary state.

[200] As per chapter 5 the settled combined sewerage system of Ho Chi Minh City is option nr. 4E.
[201] No performance measurements of Vietnamese septic tanks are available.

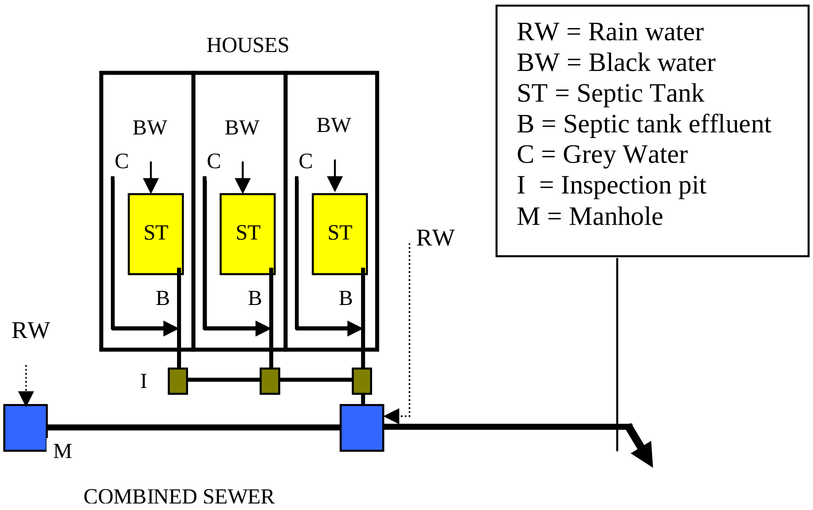

Figure 8.3 The settled combined sewer system.

In new residential areas built under a planned regime now (2008) separated sewers are constructed. The stormwater runoff is discharged to trunk sewers under the main thoroughfares in these areas. The domestic sewage is led through its own lines to a local small-scale treatment plant and the effluent of this plant discharged to the stormwater sewer. Where the small wastewater-treatment plants are not functioning well, the sewage bypasses the plant and leads to surface water pollution (chapter 9).

As pointed out in subsection 8.3.3 at high tide river and canal water flows back to the city's residential areas through the combined sewers. To combat this problem city authorities now proceed to heighten main roads, which results in reduced traffic obstruction, but obviously not in less flooding in the small alleys and yards which remain at the original level. An unknown, but certainly not large, number of households has laid out a system of individual pumping of sewage at high tide as shown in figure 8.4[202]. When the water level in the sewer is low the stand-pipe is not in place and the septic tank effluent flows by gravity to the sewers. When the water level is high and flooding threatens the removable stand-pipe is manually put in place and prevents backflow from the sewers to the septic tank. The sewage pump is automatically switched on at a certain level and discharges the septic tank effluent into the standpipe at a level higher than the water level in the manhole. A responsible of the Ho Chi Minh City Urban Upgrading project pointed out that the application of automatic return valves in large sewage pipes was considered unfeasible, as he opined that they would probably often fail[203].

[202] The system of figure 8.4. was observed once at a house in Thao Dien ward (district 2) (October 2008). The owner said he was not the only person making use of the system. He estimated the investment costs at 3 – 4 million VND (150 – 200 USD).

[203] Interview with Mr Tran Trung Hau (Assistant Director of HUU) in October 2008.

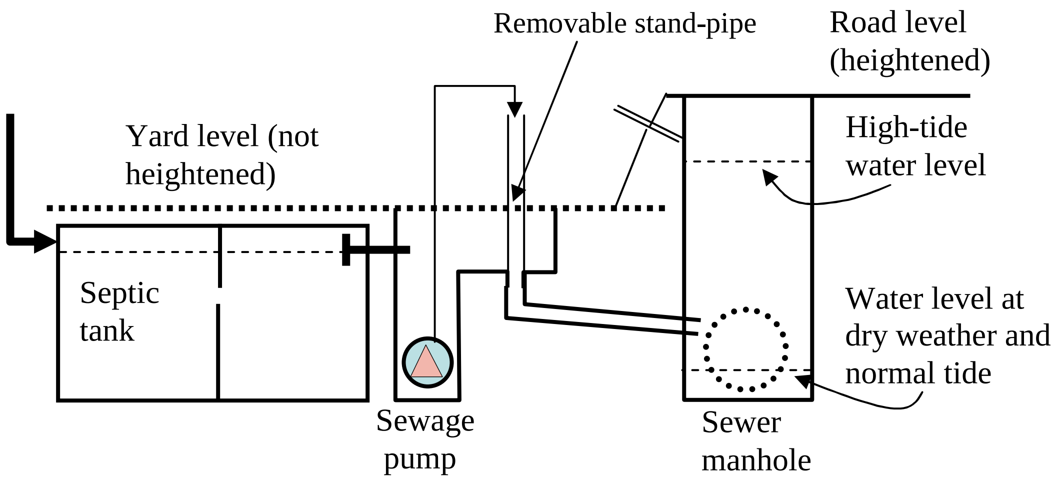

Figure 8.4 Pumped septic-tank discharge at high tide (system observed in Thao Dien ward, district 2 in 2008).

8.3.8 Wastewater treatment

The treatment of municipal wastewater, industrial wastewater and septage is briefly discussed in this subsection.

Municipal wastewater

At the moment there are still few municipal wastewater-treatment plants in Vietnam and in this respect Ho Chi Minh City is no exception. The Ho Chi Minh City's Drainage and Sewerage Master Plan of 1999 proposes a gradual coverage with stations for treatment to secondary effluent level (subsection 5.4.2). The Binh Hung plant in Binh Chanh district is the first of these large plants and has been completed in 2008 as part of the Tau-Hu – Ben-Nghe - Doi -Te Canal project[204]. It has a design capacity of 512,000 m^3/d. The plant applies primary sedimentation followed by an activated-sludge process and effluent disinfection (JICA/ Pacific Consultants International, 2000, Chapter 10).

In 2006 the Binh Hung Hoa plant with a capacity of 45,000 m^3/d has been commissioned for the treatment of the sewage of approximately 200,000 people discharged into the Den Canal (Black Canal). The realization of this plant was part of the Tan Hoa – Lo Gom project (see section 8.6). It consists of a combination aerated and natural lagoons with a total surface of 33.2 ha and is situated in Binh Tan district[205]. Though evaluated as most appropriate in the situation, the applied technology seems hardly replicable elsewhere in Vietnamese cities due to its large footprint of about 17 m^2/capita and the extremely high prices of land (Verschure et al., 2006). In addition to the two described large plants, there are many small sewage treatment plants for the wastewater of hospitals, markets, hotels, office buildings and residential areas. The experiences with these small plants are analyzed in chapter 9.

Industrial wastewater

In 2008 the number of industrial zones has grown to 13 with 6 central treatment plants (Phu, 2007). Factories with a high pollution load have to pre-treat their wastewater before discharge

[204] Author visited the Binh Hung plant in October 2008.
[205] http://www2.btcctb.org/Tan Hoa - Lo Gom/en/wwtp.htm, last accessed on November 21, 2008.

to the central sewer system. Industrial parks and individual factories outside industrial zones have to comply with industrial effluent discharge requirements as per TCVN 5945-2005 (A or B).

Septage treatment

State and private companies collect septic-tank sludge by means of small suction trucks. The total amount collected is unknown. According to Strauss et al. (1997) the most reported values of the amount of septage to be collected varies between 0.5-1 l/cap.d, which is 0.11-0.36 m^3/cap.yr. In Ho Chi Minh City with its population of 6 million, and 75% of the population using a septic tank, this would amount to a septage flow of 495,000 – 1,620,000 m^3/yr. There is (2008) one septage-processing company, named Hoa Binh in Da Phuoc (Binh Chanh district), that produces a soil conditioner from septage. Since Hoa Binh Company has moved from its former site in Tan Binh district to Da Phuoc, the company processes only 60 – 70 tonnes per day, while its capacity is 500 tonnes/day. It is said that collectors find the distance from the collection areas to the new location of the company too long, so that more than before collected septage is dumped. The produced soil conditioner is sold to plantations. In 2000 this material was sold at 30 to 50 USD/ton[206].

8.3.9 Wastewater reuse

The rural areas of Vietnam have a strong tradition with respect to recycling and reuse of wastes and wastewater in agriculture and aquaculture. Well known are the direct agricultural use of faecal matter and urine from urine-diverting dry toilets, the culture of fish in ponds treating excreta from fish-pond toilets and the VACB[207] system. The latter implies reuse of nutrients and organic matter from pig and human manure for biogas generation and fish culture. While in rural and peri-urban areas these traditions are existent but under pressure, concepts of *planned* reuse in cities are lacking. As all around Ho Chi Minh City wastewater, mostly untreated, is discharged into the surface-water system, and at the same time farmers use surface water for irrigation and aquaculture, reuse of wastewater, though *unintentionally,* plays an important role. In an assessment of agricultural reuse of municipal wastewater Rashid-Sally et al. (2004) estimate that the total agricultural area with use of wastewater for irrigation is between 6,000 and 9,500 ha around 30 Vietnamese cities. The fraction of urban wastewater that is reused in agriculture, however, is probably not more than 10%. The largest areas (in total more than 2,500 ha) are found in and around the main cities Hanoi, Hai Phong and Ho Chi Minh City. It is not known which part of the total outflow of nutrients in urban wastewater is benefiting agriculture and aquaculture. Wastewater-impacted irrigation water is mostly used in rice culture, while in aquaculture important products are Tilapia (fish) and morning glory (an aquatic vegetable) (Le and Huynh, 2005). The benefits and risks of the unplanned reuse of wastewater depend much on the degree of pollution and the type of crop. Increased concentrations of nitrogen and phosphorus in irrigation water will benefit crops and aquaculture, but high concentrations of salts, heavy metals and pathogens may have negative impacts. Vietnamese authorities are aware of the possible negative impacts, but up to now no policy has been developed. Through its nature, the described unplanned reuse moves into an ever wider area around the city, as agriculture and aquaculture have to relocate to make space for urban buildings. For several reasons, among which are land scarcity and the declining

[206] Interview with company manager in 2000.
[207] VACB stands for Vuon (garden)-Ao (pond)–Chuong (stable)-Biogas.

quality of the wastewater, the described practice of wastewater-fed agriculture and aquaculture tends to disappear (UNEP International Environmental Technology Centre and Murdoch University Environmental Technology Centre, 2002; Edwards, 2005). *Planned* reuse of effluents from wastewater-treatment plants exists in Vietnam, but is as yet insignificant. In Ho Chi Minh City effluent from a treatment plant of an industrial park is used for watering road verges in the dry season. It is unknown to what degree other industrial parks have adopted this or other effluent reuse practices. There are no plans to structurally reuse the effluents of future large-scale wastewater treatment plants in Ho Chi Minh City[208].

8.3.10 Conclusions about the water and wastewater infrastructure

In the previous sub-sections of 8.3 the water management in Ho Chi Minh City has been briefly described following the water chain from supply to reuse and the impact of polluted water on the aquatic ecosystems downstream of the city. The critical issues are summarized in table 8.6.

So far the urbanization (8.2) and the water chain in Ho Chi Minh City (8.3) were surveyed. The next section 8.4 focuses on management aspects in the domain of drainage and sanitation.

[208] Interview with Mme Pham Thi Thanh Hai (UPI, October 2008).

Table 8.6 Critical issues in water management in Ho Chi Minh City.

Sector	Critical issues of water-related infrastructure
Water Resources and Water supply (8.3.1 and 8.3.2)	Increasing water demand Dramatically falling groundwater levels in main aquifers Deteriorating quality of river water Threats of water shortages Deficient piped distribution systems Users' complaints about drinking-water quality and irregular supply
Drainage of city runoff (flooding prevention (8.3.3)	Increasing flooding and flood damage Expected rise of sea and river-water levels Insufficient drainage capacity Land subsidence No adequate policy and technical measures for low-lying residential zones
Municipal sewage (8.3.4)	Discharge of approximately 1 million m^3/d of untreated and partially treated wastewater
Industrial wastewater (8.3.5)	Large part of industrial wastewater is discharged untreated
Surface water quality (8.3.6)	Heavily polluted waterways in and around city Threat of further quality deterioration
Domestic sanitation and sewage transport (8.3.7)	Infrastructure is poor and very difficult to upgrade Infrastructure improvement does not keep pace with urbanization
Wastewater treatment (8.3.8)	Low percentage of municipal wastewater is treated Low percentage of septage is treated and reused
Wastewater reuse (8.3.9)	Reuse of wastewater serves agriculture and aquaculture and is unplanned and uncontrolled. Very little planned reuse and resource recovery

8.4 Institutions, projects and tariffs related to drainage and sanitation infrastructure

The present section first surveys the formal structure of the management of Ho Chi Minh City's drainage and sanitation infrastructure (8.4.1). Then, the principles of the Drainage and Sewerage Master Plan of 2001 and its revision undertaken in 2008 are described (8.4.2). Subsequently, an overview is given of major on-going urban upgrading projects in Ho Chi Minh City (8.4.3) and a remarks are made concerning tariffs and cost-recovery (8.4.4). The information collected in this section forms a background to further understanding and assessment of the improvement measures given in chapters 10 and 11.

8.4.1 The management of drainage and sanitation infrastructure

The management tasks related to the drainage and sewerage infrastructure are distributed according to 4 categories (in Vietnam called: levels) as shown in table 8.7. Level I-III drainage and sewerage infrastructure, that is the *main* canals and pipes, are managed by city authorities: the Urban Drainage Company (UDC) in coordination with the Urban Transport Management Department (UTMD). The latter is a section of the Department of Transportation (DT)(See Annex 8.1).

Table 8.7 Drainage pipe type and management responsibility.

Level	Characteristic of infrastructure	Political responsibility and supervision	Drainage and sewerage
I	Canals and rivers	PC-HCMC and DT	UTMD, UDC, DE
II	Trunk sewers connected to canals	PC-HCMC and DT	UTMD, UDC, DE
III	Main sewers > 800 mm diameter	PC-HCMC and DT	UTMD, UDC, DE
IV	Sewers in lanes (feeder lines)	PC-district and DT	UMD, DPWC

DT is the city's sector department in the domain of transport and communication and constitutes the provincial/city representation of the national Ministries of Transportation and Communication (MTC) and the Ministry of Construction (MOC). The canal and sewer maintenance at the levels I-III is carried out by 7 drainage enterprises (DE) resorting under UDC. Level IV sewers in the residential areas are laid out and maintained by Public Works Companies of the districts (DPWC) resorting under the Urban Management Divisions (UMD) of the districts. At city level the People's Committee (PC-HCMC) is the main political authority responsible for the City and District master plans in various sectors, among which sewerage projects. The PC of Ho Chi Minh City, though powerful, requires for its master plans and major infrastructure projects approval from the national government.

In addition to the preparation, implementation and operation of drainage infrastructure at city level, the Department of Transportation (DT) is also tasked with the approval of level IV projects of the districts. The Department of Natural Resources and Environment (DONRE) is responsible for land and water resources management and the enforcement of environmental regulations and policies, such as effluent requirements for industrial and residential wastewater treatment plants. DONRE is the city's representation of the Ministry of National Resources and Environment. A new organization in the sector of drainage directly under the People's Committee is the City Flood Prevention Centre. This Centre has been set up in 2008 to address the problem of flooding in an integrated way. An overview of the organizational structure related to urban environmental infrastructure in shown in the organogram of Annex 8.1.

From 1995 on the Vietnamese government has issued regulations for wastewater management and the protection of surface water, such as the industrial effluent discharge and surface water standards of 1995 (for industrial effluent: TCVN 5945-1995, for surface water TCVN 5942-1995) and a revision of the industrial effluent standards: TCVN 5945-2005. Important in the context of domestic wastewater is the standard for effluents of residential areas and the public and commercial sector issued in 2000 (TCVN 6772-2000). According to these documents industrial and domestic wastewater has to be treated to secondary level[209]. As long as central wastewater treatment is unavailable, this policy implies the establishment of many on-site wastewater treatment plants. The policy related to these plants is evaluated in chapter 9.

8.4.2 The Drainage and Sewerage Master Plan of Ho Chi Minh City

The HCMC People's Committee, supported by its expert institutes (UPI, DOC, DT, DONRE and others) directs the city's development by means of city and district master-plans. These plans define the intended use of the land and the main lines of communication and accessory infrastructure, such as drainage canals and sewerage pipes.

[209] The permitted effluent quality depends on loads (TCVN 6772-2000) and on the flow of the receiving water (TCVN 5945-2005); see appendix 1.

In the late 1990s the Department of Transportation and Public Works, predecessor of the Department of Transportation, has prepared a Drainage and Sewerage Master Plan for Ho Chi Minh City, which was approved in 2001 (JICA/ Pacific Consultants International, 1999f). The plan departs from the following principles: flow control of Saigon and Dong Nai Rivers through the upstream dams and reservoirs used for irrigation and generation of hydropower, improvement of urban drainage by widening and dredging existing canals. Excessive runoff has to be controlled by retention basins. As polder dikes and pumped drainage were deemed too expensive at that time, the plan recommends building new residential areas on heightened land. As mentioned before a minimum level of 2 m above MSL should be guaranteed. In low areas 1.5 to 2 m of sand/soil would have to be brought onto the land prior to building, so that the land is not only protected against flooding but also sewage and stormwater can be drained by gravity. For sewerage and sanitation three concepts are distinguished:

1. In inner city districts the existing combined sewer system will be extended. Big interceptor sewers and pumping stations will convey the wastewater to 9 large wastewater treatment stations located in the different catchment basins of the city.

2. In new urbanizations in districts 2, 7, 9, 12 and Thu Duc stormwater and sewage will be collected in separated sewer systems. The sewage will be treated in centralized wastewater-treatment stations. Stormwater will be discharged without treatment.

3. Areas outside the inner city with population densities less than 200 inhabitants/ha will not be connected to the large sewer networks, but will have household on-site systems. The plan suggests the septic tank with anaerobic upflow filter as the best on-site option. According to the Plan these systems would generate 92,000 m^3 of sludge annually.

The 9 planned large wastewater-treatment stations vary in capacity from 55,000 – 500,000 m^3/d. Their design will be based on a form of the activated-sludge technology with sludge dewatering. Their realization is anticipated to last from 2006 to about 2020. The design of the biggest plant that is going to serve the central districts envisages an enhancement of the treatment efficiency by stepwise reduction of the sludge loading rate. The surplus sludge will be dewatered by means of centrifugation (JICA/ Pacific Consultants International, 2000). The Master Plan suggests that no further stabilization of the sludge is required. This could be justified pointing at the low influent BOD_5 and the general use of septic tanks as pretreatment step. The plan does not detail the methods of treatment and disposal of the produced biosolids or of removal and recovery of nutrients N and P from the wastewater.

For drainage canals, flood detention basins, pumping and wastewater-treatment stations much land will have to be reserved especially in the Southern and South Eastern downstream zones of the city. This land was still mainly agricultural land at the time of writing the Master Plan, but it is uncertain if not informal building will have swallowed the land by the time the infrastructure has to be laid out[210].

[210] Concern about the availability of land was expressed by several interviewed urban specialists.

By 2008 the practical conditions and new insights require a revision of the old Master Plan. The revised plan under preparation (2008) has extended its scope to 2025 and an area of 2,000 km^2 instead of 650 km^2. Important alterations to the existing Master Plan are the following[211]. The number of wastewater-treatment stations in Ho Chi Minh City will grow to 12 (was 9 in the plan approved in 2001) and their discharges will have to comply with the requirements of TCVN 5945-2005, instead of TCVN 5945-1995. This number of stations does include the already existing Binh Hung Hoa plant in Binh Tan district. The dry weather flow-rates are higher than before, as the average domestic drinking-water consumption is expected to increase to 200 l/cap.d over the entire area, and the number of industrial zones will continue to grow. Further, the consequences of climate changes, namely rise of sea level and higher frequency of exceptional storm and rainfall events, will be taken into account. The option of dikes and pumped drainage was put on the agenda and has resulted in a new approved project in 2009. Also the possibilities of rainwater harvesting are being studied. The use of local-area wastewater-treatment plants will remain required as long as the new large-scale plants are not realized. Wastewater reuse will not be part of the new Master Plan.

8.4.3 Major projects to improve urban drainage and wastewater infrastructure

Five major projects constitute the answer to the problems of flooding and pollution in Ho Chi Minh City (table 8.8). The projects include not only renovation of the drainage and sewerage system, but also major slum relocation and upgrading projects.

The Nhieu Loc – Thi Nghe canal project aims at upgrading and environmental improvement in central districts of the city. Contrary to its time planning, it will probably not be completed in 2009 as the construction works have suffered serious setbacks. The experiences in this project have been assessed as very positive (Lang, 2006). The large Tau-Hu Ben-Nghe Doi-Te Canal project cooperates with the, also Japan funded, East-West Highway project, and will be continued after 2009 in a second phase. The Hang Bang Canal Rehabilitation Project is part of the HCMC Environmental Improvement Project (1702-VIE).

The total planned expenditure on the realization of the Drainage and Sewerage Master Plan up to 2020 has been estimated at 2.92 billion USD (about 380 USD/capita) and the operational cost at 11.4 million USD/yr (about 1.44 USD/cap/yr) (PC HCMC, 2002). Where deadlines of projects are exceeded, donors tend to discontinue their funding and the Vietnamese government will have to fund the completion of the project in another way. The experiences of one of these projects, the Tan Hoa – Lo Gom project, are discussed in section 8.6.

Independent from the ongoing large projects groups of households affected by severe infrastructure problems may direct an improvement request to the ward. Such requests meet a positive response where the ward has already planned an improvement, but in other cases the problems may remain unsolved for many reasons. Often communities improve infrastructure through their own means collected from the households with the ward in a supervisory role. As this approach contributes significantly to neighborhood upgrading, its possibilities and constraints should be studied in more detail.

[211] Data about the revision of the Drainage and Sewerage Master Plan were obtained in an interview with Mme Pham Thi Thanh Hai, Vice-Director of UPI (October 2008).

Table 8.8 Environmental upgrading projects in Ho Chi Minh City (author's data collection).

Project	Benefiting area (km^2)	Benefiting districts	Duration (yr-yr)	Budget	International donor/bank
Nhieu-Loc Thi Nghe Canal[212]	33	1, 3, Phu Nhuan, Tan Binh, Binh Thanh	1998-2009	320 mln USD	World Bank
Tau Hu -Ben Nghe – Doi Te Canal[213]	31	1, 3, 4, 5, 6, 8, 10, 11, Tan Binh	2002-2009	410 mln USD	JBIC
Tan Hoa – Lo Gom Canal[214]	19	6, Binh Chanh	1998-2006	20 mln Euro	Belgian Technical Cooperation
Hang Bang Canal[215]	5.2	5, 6, 11	2000-2007	25 mln USD	ADB
Ho Chi Minh City Urban Upgrading (HUUP)	n.a.	6, 8, 11, Tan Binh, Binh Chanh	2004-2012	300 mln USD	World Bank
Ho Chi Minh City Flood Control Project[216]	n.a.	All districts	2009-2025	650 mln USD	Donor not available

8.4.4 Tariffs

The public utilities in Vietnam find themselves in a transition from full subsidization by the state to becoming market parties with full cost recovery. In 2008 the costs of public utilities like water supply and drainage companies in Ho Chi Minh City are partly covered by state subsidies and partly by tariffs levied on users.

The tariffs households pay for drinking water are subject to a progressive system in which the price per m^3 increases stepwise with the consumption. The base rate up to a consumption of 4 m^3/pers. month was 1,300 VND/m^3 (0.094 USD/m^3) in 1998 (JICA/ Pacific Consultants International, 1999e, p K-24) and has increased to 2,700 VND/m^3 in 2008 (0.169 USD/m^3)[217].Water tariffs paid by industries are higher (3,100 VND/m^3 in 1998). The revenues are probably just sufficient to cover the running costs of the treatment and distribution system.

For sewerage and wastewater treatment households contribute a surcharge of 10% on the drinking-water bill, so that the amount paid is proportional to the drinking-water consumption and domestic sewage production. As of 2008 the surcharge for households amounts to 270

[212] (Camp Dresser McKee International, 1999).
[213] (JICA/ Pacific Consultants International, 1999f).
[214] Personal communication with Mme Le Dieu Anh, Vice-Director of PMU 415 (2005). The project will be continued with a 400 mln USD investment in drainage and urban upgrading in districts 6, 11 and Tan Binh.
[215] Personal communication with Mme Bui Thi Lan Huong, Vice-Director of PMU 1702 (2005).
[216] Personal communication with Dr Nguyen Trung Viet of DONRE (July 19, 2010).
[217] Personal communication with Dr Le Vo Phu (Ho Chi Minh City University of Technology, 2009).

VND/m^3 or approximately 6,000 VND/hh/month. According to a survey by the JICA study team ín Ho Chi Minh City in 1998 the households willingness-to-pay for sewerage amounted to 9,000 VND/hh/month (0.65 USD/hh/m) or 0.46% of the average household income.
Residents not receiving their water from the supply network operated by the central Water Supply Company (SAWACO) or residents whose water is not metered do not pay the mentioned tariffs. This works as an –undesirable- incentive to private on-site groundwater extraction. Based on a costs-revenues analysis of the investments in the Drainage and Sewerage Master Plan the Environmental Management Strategy for Ho Chi Minh City to 2010 recommends a sewerage fee for residents of 180,000 VND/hh/yr (12.8 USD/hh/yr) which was at the time an increase by a factor 1.6 over what most people were willing to pay (People's Committee of Ho Chi Minh City, 2002, p 11-4)[218] and nearly 3 times what households paid in 2008. This heightened fee would cover the running and a minor part of the replacement costs of the system; the remaining replacement and the full capital costs would still have to be supplied by the government.

8.5 Unplanned urban development and infrastructure: stakeholders' views

As shown in section 8.2 large parts of Vietnam's main cities have developed without plans for land heightening, housing, roads, drainage, sewerage and space for trade and recreation, or without giving heed to plans that exist. In order to obtain more insight into the consequences in the domain of infrastructure this section summarizes studies about the following issues:

1. residents' opinions on environmental problems in Ho Chi Minh City (8.5.1),
2. infrastructure development and residents' opinions in An Lac ward of Binh Chanh district and ward 19 of Tan Binh district, both recently developed unplanned neighborhoods in Ho Chi Minh City (8.5.2).
3. experiences of contractors with construction and maintenance of sewers (8.5.3)

This section is concluded with a summary of causes and solutions of drainage and sanitation problems (8.5.4).

8.5.1 Residents' opinions about environmental problems

In the framework of the formulation of an Environmental Management Strategy for Ho Chi Minh City surveys were carried out in 3 urban wards and 2 suburban hamlets of the city (People's Committee of Ho Chi Minh City, 2002). Samples of residents were asked to list and rank perceived environmental problems and measures to address these problems. Residents listed 9 different key environmental issues, among which on average deficient solid waste collection, air pollution, deficient drainage (flooding), and canal pollution were found the most pressing problems In some zones deficient drinking-water supply is a high-ranking problem as well, but not in the selected zones. An overview of the problem ranking is shown in table 8.9.

[218] The willingness to pay for sewerage and wastewater treatment was found to be 9,000 VND/hh. Month. (JICA/ Pacific Consultants International, 1999e, p K-25). In 1999 the exchange rate of the USD to the VND was 14,000 VND/USD, in 2008 it was 16,000 VND/USD.

Table 8.9 Priority environmental problems as perceived by residents in several communities in Ho Chi Minh City (1 = highest priority) (Source: (People's Committee of Ho Chi Minh City, 2002, chapter 5).

Area	Solid waste collection	Air pollution	Deficient drainage	Canal pollution	Deficient drinking-water supply
District 2	1	3	2	5	4
District 3	1	2	3	4	5
District 6	2	1	3	2	Very low
Overall	1	2	3	4	7

A similar study has not been repeated since, but it could well be that air pollution is perceived as the most aggravating problem in 2008, since the traffic has tremendously increased during the past 10 years. The big environmental improvement projects mentioned above do address the problems of deficient drainage, flooding and canal pollution, but as most of them are not completed yet (2009), or have a limited impact, no major improvements have been achieved, except in the domain of slum clearance.

Staff of local environmental authorities were asked as well to list and rank their key environmental problems. They mentioned the five problems shown in table 8.9, but not four other ones residents found important. These were traffic jams, noise, food poisoning and pollution caused by industrial activities. The surveys showed the importance of involving residents in the problem analysis.

8.5.2 Drainage and sanitation infrastructure in unplanned urban communities

The consequences of unplanned building on infrastructure development in two unplanned neighborhoods of Ho Chi Minh City were studied by Gordillo-Manzano (2004).

The case of sub-district 6 of An Lac ward

At the moment of study (fall of 2003) sub-district 6 of An Lac Ward comprised about 2,400 households. 70% of the houses in the area were built after 1990. No detailed income figures were available, but apparently the area was not a slum, but a rather average new housing area, where the houses are made of brick and concrete and 85% of the households possessed a television, a motorbike and a refrigerator or fixed telephone. Among the 109 households interviewed 35% had an official house-ownership certificate and 20% a land certificate, meaning that the majority did not possess these documents which testifies to the informal character of the settlement process. The main reasons given for not having these documents were the long duration and high cost of the procedures and the lack of required other documents. Among the interviewed households only 18% had piped water supply. The other households either used water from wells (40%) or water vendors (39%) (table 8.9). The people in the area complained about the quality of the water from the wells and the high price of the water from the vendors. The dominating sanitation system was the pour-flush or cistern-flush toilet followed by a septic tank (94% of the households) that discharges to a public sewer (62%). Alternatively, discharges of toilet water took place into ponds, canals and soakage pits (33%). This discharge into the environment was possible since the neighborhood still had open spaces. Dry toilets (pit latrine and double-vault composting toilet) were used also, but in very small numbers.

The drainage situation in the area was precarious. Most households had applied a certain heightening of their land prior to building with a reported average of about 80 cm, but the height differences between households were considerable. Roads were in general unpaved. 70% of the households reported to suffer from flooding. Some blamed it to sewer clogging, but more probably the sewers that existed had not been designed to evacuate stormwater. Out of a list of infrastructural improvements the interviewees gave highest priority to water supply, followed by flooding prevention on the second and connection to the sewer system on the third place.

The case of ward 19 in Tan Binh district
The study in ward 19 of Tan Binh district took place under the supervision of the Center for Social Development and Poverty Reduction in Ho Chi Minh City in the framework of the Tan Hoa – Lo Gom Canal project (see 8.6). Ward 19 has a surface area of 1.83 km^2 and a population of approximately 48,000 (1999 census). Several parts of the ward apparently have been laid out without plan. Especially striking are the narrow streets, where even a light motorbike can hardly pass. Most (70%) houses in the area were built after 1992. The survey included 285 households with an average number of wage earners of 2.2 per household and a household income of 2.8 mln VND/month (= 184 USD/m). Nearly all the households surveyed were owners of their house (92%), but only 28% had an official ownership certificate and 8% a land title-deed. Most of the households got both water for drinking and for household purposes from wells and boreholes (71%); 15% was served by a private piped water-supply network (table 8.9). The predominant sanitation system was the flush-toilet followed by a septic tank (66 %). Out of the 66% households with septic tank two in three discharged to a public sewer (44% of the total) and the rest (22% of the total) to a local canal or the soil. In 31% of the households the flush-toilet discharged to a public sewer without pretreatment in a septic tank. By virtue of its elevation and possibly more widely branched sewer grid, flooding in ward 19 is less of a problem than in sub-district 6 of An Lac ward. Only a few houses whose floors were lower than street level or that were situated in ill-sewered corners of the ward suffered from flooding at strong rain events.
When asked about the main problems in the area, poor infrastructure scored higher than poverty, poor health or insecurity. In particular water supply, better sewerage and garbage collection were the priorities for the inhabitants of ward 19. Among the households that had suffered from diseases in the past year (64% of the sample), 61% thought these diseases were due to the conditions of the area where they live.

An overview of the infrastructure data of the two study areas is presented in table 8.10. The figures represent the percentages of the households surveyed (Gordillo Manzano, 2004).
In both areas the environmental conditions were considered seriously deficient, due to a combination of inadequate road, drainage and sanitation provisions. With regard to sanitation there is on the one hand the problem of on-site discharge of wastewater into surface water and soil in a densely populated area, and on the other the considerable construction and maintenance deficiencies of the sewers. Flooding problems are serious is An Lac ward and less so in the more elevated and better sewered Ward 19 of Tan Binh. Flooding problems are due to inadequate drainage. The lay-out of proper drainage systems is complicated by insufficient and unequal heightening of the land prior to building.

Table 8.10 Water-supply and sanitation infrastructure in two unplanned areas of Ho Chi Minh City.

Infrastructure	% of households surveyed in An Lac Ward (Binh Chanh)	% of households surveyed in Ward 19 (Tan Binh)
Piped water supply	18	15
Drinking-water from wells	40	71
Drinking water from vendors	39	10
Pour-flush toilets in the house	97	98
Discharge of wastewater to sewer	62	75
On-site disposal of wastewater	33	22
Flooding during previous year	70	6

8.5.3 Constraints of drainage at ward level

Through interviews with designers, contractors and district authorities Stamper (2004) collected experiences with the feeder sewers in the wards (so-called level-IV sewers). While the households are responsible for their septic tank and the connection to the sewer, the sewer itself is usually laid out by District Public Works Companies once a certain housing density has been reached (table 8.7). The experiences often show the following problems. Lanes in unplanned neighborhoods lack space for sewer lines. The contractor has to work without detailed maps and clear plans for the area and he himself has to decide about the location of new feeder lines. New lines are laid out in unplanned streets where (soon) afterwards many houses have to be (partly) demolished to give way to a wider road, with the effect that the sewer lines have to be redone. Up to now the general principle is to avoid pumping of wastewater, also in flat low-lying neighborhoods, in order to reduce costs, but the available slope is too small to guarantee unhindered gravity flow, even where septic tanks have eliminated most suspended solids from the toilet water. This lack of slope is due to insufficient heightening of the land prior to building. Sewers lines often cross other subterranean infrastructure by means of siphons that often clog. The contractors working on level-IV sewers in unplanned neighborhoods are stimulated to use low-cost methods, but also to maintain a minimum acceptable construction standard. Examples are the use of clay pipes instead of concrete or PVC and pipes of the smallest acceptable depth, slope and diameter. There are problems with substandard work, due to a lack of surveillance about the proper application of standards. The work's formal design lifetime is 10 years, but in practice it often has to serve for a much longer time, so that malfunctioning can be expected. With regard to maintenance a chief problem is lack of funding and consequently inadequate means to carry out maintenance. For example Drainage Enterprise 6 is in charge of 7 districts of Ho Chi Minh City, yet it has only 70 workers who mainly have to solve drainage problems with their bare hands. Although since around 2005 a 10% surcharge on the drinking-water bill was levied destined to recover the costs of sewerage, the generated revenue was by far insufficient to cover the entire budget for sewerage and wastewater treatment activities[219].

8.5.4 Conclusions of the surveys

Section 8.5 investigates the way the critical issues like flooding and pollution manifest themselves in the neighborhoods and in particular in the unplanned neighborhoods. Surveys

[219] Interview with Mr Nguyen Bao Khanh (UDC) in 2005.

have shown that the infrastructure conditions in the areas of unplanned building are deficient. While according to the Environmental Management Strategy (People's Committee of Ho Chi Minh City, 2002) the involved residents ranked the priority of improvements of drainage and sanitation higher than water supply, the outcomes were opposite in the case of An Lac ward in Binh Chanh district and ward 19 of Tan Binh district. Apparently, residents' priorities differ strongly from place to place. Especially, in recently constructed neighborhoods water supply may still be inadequate and is then a high priority to the residents.
The pollution and flooding in the unplanned neighborhoods are caused by deficient roads, drainage and sanitation provisions and solid-waste collection, exacerbated by an often low environmental awareness of the residents. The lay out of better drainage systems in low-lying unplanned areas is complicated, if not impossible, due to inadequate landfilling prior to building, lack of space and budgetary constraints. Due to lack of capacity and clear guidelines local authorities often have great difficulties to solve the mentioned problems. In this situation groups of neighbors often take the initiative to address the most pressing problems by their own means. This may temporarily and locally alleviate problems, but usually proves insufficient without other solutions at a higher spatial level.

8.6 Lessons from the Tan Hoa - Lo Gom project

8.6.1 Introduction

As shown above the infrastructure problems are strongly connected to the deficient housing conditions in many parts of the city, which in their turn were caused by lack of planning and guidance during the construction phase. It is clear that these problems can only be overcome by major urban improvement. In section 8.4 the most important ongoing urban environmental improvement projects are briefly described. It is of great importance for the city to learn how such urban upgrading, including improvements of deficient sanitation and drainage infrastructure, should be carried out.
The first project which has experimented boldly in this domain is the Tan Hoa – Lo Gom sanitation and urban upgrading project (1998-2006). After a description of the project its most important lessons, especially those in the field of housing and sanitation and drainage are briefly presented.

The Tan Hoa - Lo Gom and Den canal zone on which the project focused are densely populated, flood-prone and mainly low-income urbanizations at the west side of Ho Chi Minh City (District 6, district Binh Tan) encompassing a population of about 900,000 over an area of about 20 km^2. The canal and its subsidiary canals with their total length of 19 km are one of the most heavily polluted drainage systems in the city (BTC/CTB et al., 2003, chapter 8 p 10/11). At the start of the project the canal's embankments were cramped with the precarious shacks of thousands of poor squatters, most of them involved in informal livelihoods. Due to absence of sanitation and solid-waste collection services in these squatter areas the inhabitants dumped their wastes into the canal which contributed to its pollution and obstruction. A survey showed, that complete rehabilitation of the canal's embankments would require the relocation of 1,269 households (BTC/CTB et al., 2003, chapter 8 p 6).
The Tan Hoa - Lo Gom project has attempted to address these problems in an integrated and humane way, i.e. not only addressing the physical (canal enlargement, demolition of unwanted squatter housing) and environmental problems (avoidance of dumping of wastes and untreated wastewater), but also offering solutions of better housing and livelihoods for

those who had to be resettled, and perhaps most important: making heard the voice of the city's poor (Anh et al., 2007).

The project included the following main components:

- Reconstruction of the canal embankment and enlargement for better drainage;
- The Binh Hung Hoa wastewater-treatment project;
- Solid waste collection and construction of a small transfer station;
- Ward 11 of district 6 upgrading and an apartment resettlement pilot project;
- Sites and services resettlement pilot project;
- Socio-economic activities supporting the housing and infrastructure projects.

It is judged as most relevant that this project has introduced various housing alternatives and new ways of looking at urban upgrading, and has built up experience with community participation, which was scarce in Vietnam before the project (Verschure et al., 2006). Community participation in decision-making had acquired a legal basis in Vietnam through the governmental Decree 29 issued in 1998 in answer to failing governance and popular unrest. This decree defines information to the public, consultation of involved stakeholders, seeking of popular approval for government projects and project supervision by the people as important elements in decision-making processes at commune and ward level (Mattner, 2004). As such the Tan Hoa – Lo Gom project was one of the first projects to implement Decree 29.

8.6.2 Housing alternatives

As shown above Ho Chi Minh City has many residential zones with severe infrastructure problems that have to be strongly improved. The project became aware that the generally adopted concept of urban improvement among Vietnamese authorities encompasses slum demolition and resettlement of the dwellers to high-rise apartment buildings, often far from the site of clearing, or self-resettlement. The thus cleared land is then used for (expensive) high-rise buildings or other destinations.

This mode of urban upgrading has demonstrated several important drawbacks: it is expensive, the relocated people are cut off from their original livelihoods, and their new high-rise apartments do not provide the space for informal income-generating activities. Consequently, many relocated people loose their livelihoods and end up in slum areas elsewhere in the city.

The Tan Hoa - Lo Gom project introduced several other modes of urban upgrading:

- On-site upgrading of housing and infrastructure;
- Resettlement in sites and services projects;
- Resettlement in apartment buildings in the area of origin and designed for people; from the informal areas.

These three modes of urban improvement are briefly discussed here.

On-site upgrading means that the zone's water supply, solid-waste collection, sanitation, roads, sewers, street lighting, etc are improved with a minimum of destruction of existing houses and resettlement. Demolition and resettlement usually cannot be avoided completely, as roads in areas of popular building are extremely narrow. Often they are not more than 1 meter wide. They must be widened to give access to emergency services such as ambulances and fire engines to a width of at least 4.5 m. The process of determining the new center line of roads and therewith the identification of the houses that have to disappear is a crucial part of the community consultation[220]. In the Tan Hoa - Lo Gom project this form of neighborhood improvement has included 166 houses at a cost of 325 USD/household. It took place in ward 11 of district 6.

In a sites and services projects new residents can buy or rent a plot of land and subsequently build (or have built) their own house. The building land is provided with all basic infrastructure, like roads, green spaces, water supply, electricity and sewers, and services (schools, clinics, post office). In the Tan Hoa - Lo Gom project the sites and services scheme involved 199 families. The houses in the project are row houses, consisting of a ground floor and two stories on a 40 m2 plot. This type of house has no yard. The cost of the new houses, including land, amounted to 7,240 USD/house. A drawback in Tan Hoa - Lo Gom was that no suitable land for the sites and services pilot project could be found close to the upgrading area along the canal, so that this pilot project had to be located at a distance of 8 km. Consequently, the resettlement to the new housing area just as the demolition and relocation projects mentioned above caused some loss of jobs and businesses. However, the houses in this scheme offered better opportunities to start a new (work)shop than the high-rise apartment buildings.

In the Tan Hoa - Lo Gom project much effort has been made to design and construct a low-rise apartment building that would be suitable for the relocated people. In particular this meant that the buildings would give easy access to the streets and have space for commercial activities. This building is located in the upgrading area along the canal. In addition to the apartment building a new market place and community center were established. This mode of resettlement involved 72 households and the average costs of the apartments was 8,100 USD each.

Strengths of neighborhood upgrading as compared to demolition and resettlement are its relatively low cost and absence of negative impact on social and economic networks and activities. The process of community consultation and participation strengthened social coherence and status of the residents. In the case of the Tan Hoa - Lo Gom project this approach did not succeed to solve the problem of flooding in the upgraded neighborhood.
The sites and services approach meant an important improvement of the beneficiaries' living environment and social position. A very pleasant neighborhood was created. It was learnt that the project should have put more attention to the problems of residents of the areas surrounding the project, so that resentment and jealousy of these residents could have been avoided. The average costs of the housing in the sites and services project was considered high, so that many families have run into debt. According to the evaluation report cost could have been reduced by enabling incremental building and a larger degree of self-construction by the homeowners (Verschure et al., 2006). Although the project had taken much care to design an apartment building appropriate to the new dwellers, they felt that there was still a lack of sufficient space for their economic activities. City authorities were not completely satisfied as well. They found the population density of the area of the apartment building far

[220] Interview with Mr Tran Trung Hau (Assistant Director of HUUP) (October 2008).

too low. The evaluation report states that projects with row houses, as built in the sites and services project, can reach very high densities and seem to be preferred by the residents, and that high-rise buildings are suitable only to people with formal jobs (Verschure et al., 2006).

Through the approach chosen in the Tan Hoa - Lo Gom project city, district and ward authorities have learnt about other possibilities than demolition and resettlement and affected residents are given a choice. These lessons have proven of much importance to the Ho Chi Minh City Urban Upgrading Project (table 8.4) which carries out urban upgrading in nearly all districts of the city[221].

8.6.3 Sanitation, drainage and wastewater treatment

The intervention zone of the Tan Hoa – Lo Gom project in district 6 and also the location of the sites and services project are flood-prone areas. The stilt houses situated on the canals are equipped with so called hanging-hole toilets from which the residents defecate directly into the canals. These houses are too small to install flush toilets and sewers. Other houses in the area have pour-flush toilets and septic tanks which discharge to combined sewers. These sewers eventually also end in one of the city's surface waters. What did the project achieve with respect to the area's sanitation and drainage problems?

The usual approach to overcome flooding in existing residential zones is to heighten the main roads and improve sewerage, so that at least the traffic is not affected by flooding. The consequence is, however, an exacerbation of the flooding problems in adjacent un-heightened areas and within the houses. The usual solution is that homeowners heighten their ground-floors taking the new road level as reference. This is of course a costly procedure and often leaves the households with the problem of wastewater discharge at high tide. Evaluators judged the incapacity to solve flooding problems a shortcoming of the Tan Hoa - Lo Gom project (Verschure et al., 2006)[222]. Within the sites and services project the drainage situation was good, as the land was sufficiently heightened and sewers had a sufficient gradient, but flooding increased in the surrounding areas much to the detriment of the residents there. Although pumped drainage is already applied at some sites of district 6, this solution to flooding did not reach the upgrading zone of the Tan Hoa - Lo Gom project. As far as stilt houses along the canals were removed, direct disposal of wastewater and nightsoil has come to an end, but in remaining houses this practice goes on as their inhabitants do not have an alternative. This problem will be overcome in the future by installing public toilets near the houses along the canals (CENTEMA and DENTEMA, 2008). This solution was decided upon using the SANCHIS multi-criteria tool developed in chapters 3 to 7. The details of this process as applied to district 6 are described in chapter 11. The Tan Hoa – Lo Gom project also included the realization in 2006 of the first large municipal wastewater-treatment plant in Ho Chi Minh City. This plant is described in subsection 8.3.6.

8.6.4 Outlook on a sustainable environmental infrastructure

This section investigates the extent to which the Tan Hoa – Lo Gom project demonstrates the technological and institutional transformations typical for sustainable environmental infrastructure development (chapter 2, section 2.5):

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[221] Interview with Mr Tran Trung Hau (Assistant Director of HUUP) in October 2008.

[222] Interview with Mrs Le Dieu Anh (former Vice-Director of Project Management Unit 415, charged with the execution of the Tan-Hoa Lo-Gom project) in October 2008.

- Technological mixes according to the conditions of the communities instead of monolithic infrastructure solutions (from centralized to mixed infrastructure);
- Saving natural resources and reducing emissions through closing material cycles (from unrestricted use of resources to prevention and closed material cycles);
- Involvement of users collectives and the private sector instead of central provision by the state/city or district (from centralized state-led planning to multi-actor planning);
- Mixed infrastructure management (from centralized state-led management to multi-actor management).

Mixed technical infrastructure
As shown above the project has in particular worked on new housing options for the poor and as such contributed to new concepts for a more diverse technical infrastructure. The housing realized in the project has become cheaper and socially appropriate through relaxation of government rules and regulations. The evaluation report recommends further exploration of flexible and incremental regulations and the development of typological alternatives for housing and related infrastructure (Verschure et al., 2006). In the implementation of sanitation and drainage infrastructure the Tan Hoa - Lo Gom project has followed the requirements of the Sanitation and Drainage Master Plan of Ho Chi Minh City (BTC/CTB et al., 2003, chapter 8 p 1). The Master Plan prescribes replacement of hanging-hole toilets by regular pour-flush or cistern flush toilets. For densely populated areas like district 6 the Master Plan further introduces separated collection of stormwater and sewage and large-scale catchment-size wastewater treatment in addition to the existing systems of public toilets and flush toilets cum settled combined sewers. In the Tan Hoa - Lo Gom project hanging-hole toilets have been removed and separated sewerage has been implemented in the sites and services project[223]. It can be concluded, that the project has led to an increase of the applied technical sanitation and drainage options, though this increase did not go beyond the guidelines of the City's Master Plan.

Closing material cycles
The applied technical drainage and sanitation systems limit the production of valuable materials from sewage to soil conditioners based on septic-tank sludge. It is as yet unknown to what extent septic-tank sludge in the project intervention area is in fact reutilized. As reported in subsection 8.3.8 the valorization of wastewater in Ho Chi Minh City is still at a low level and it was not an objective of the Tan Hoa - Lo Gom project.

Multi-actor planning
Backed by the Decree 29 the Tan Hoa - Lo Gom project has been early in Ho Chi Minh City to apply community consultation and participation in planning of urban upgrading at this scale (subsection 8.6.1). Ward and district staff has increased its capacity to carry out projects in a new way. The evaluation report states, however, that much work remains to be done at the level of city authorities to increase willingness and capacity to take the road of community involvement in future upgrading projects (Verschure et al., 2006). The same report also proposes to move on from consultation and participation of beneficiaries to co-ownership. Such co-ownership would require a community savings and credit programme, so that communities raise their own means for investment. In this respect the report refers to

[223] Site visit with Jozef de Smet, resident engineer of the TAN HOA - LO GOM project (April 2005).

experiences in other Asian countries where local non-governmental organizations play a strong role in neighborhood upgrading. An important problem is the absence of a housing and infrastructure financing system suitable for the poor, which also explains why there are as yet hardly any housing projects destined to low-income groups in Ho Chi Minh City. The possibilities of public-private-community partnerships to fill in this gap are presently being explored[224].

Multi-actor infrastructure management
The maintenance of housing is taken care of by the owner which can be the state, but usually is the individual house-owner. Road, drainage and sanitation infrastructure management is a task of public works companies of the districts (DPWC, subsection 8.4.1). The Tan Hoa – Lo Gom project was not sufficiently able to ensure community management of the housing projects and infrastructure. The evaluation report suggests that community management could contribute to social cohesion, and more efficiency, especially in the management of the infrastructure that was not laid out by the habitual state companies (Verschure et al., 2006).

8.6.5 Conclusions about the Tan Hoa – Lo Gom project

The Tan Hoa – Lo Gom project has made important steps towards sustainability, in particular in the institutional domain. Activities have been undertaken in the field of housing and infrastructure diversification, so that more appropriate systems have been created than could result from a top-down approach. Overcoming flooding appeared the most difficult infrastructure problem in the project zone as it would have required major interventions in land heightening, water retention basins and/or run-off pumping. Also steps have been taken to bring the state-actors and system end-users together in the planning process. Only at a later stage the project staff has become aware of the need of community self-management, an item which has been clearly advocated in the final evaluation document (Verschure et al., 2006). Introduction of new concepts of closing of material cycles has not been an objective of the project. As such it was typically acting on a brown and not a green agenda.

8.7 Strengths and weaknesses of the sanitation and drainage practice

The present section summarizes the diagnosis presented in the previous sections of this chapter. Ho Chi Minh City can be characterized by a fast population growth of about 3.5% per year and an economic growth of around 10% per year, driven by massive domestic and foreign investment and creation of job opportunities in industry and services. This development takes place against a background of a still grossly inadequate physical infrastructure of transportation and environmental protection, while authorities are overwhelmed by the pace of the developments and are seeking desperately for adequate coping strategies. As a consequence the city faces severe problems of air pollution, solid-waste management, groundwater over-extraction, pollution of its waterways and frequent flooding to mention but a few of its environmental problems.

Although the problem analysis presented in this chapter naturally seeks to highlight weaknesses to obtain a basis for future improvements, the situation in Ho Chi Minh City, and Vietnam in general, also shows strengths and opportunities:

[224] Interview Mrs Le Dieu Anh, former vice-director of the Tan Hoa - Lo Gom project (October 2008).

- A political and economic drive to improve housing, infrastructure and urban services;
- A growing effort to improve the legal and institutional framework for urban management based on lessons about past deficiencies;
- International support in the form of various forms of credit and grants;
- Several ongoing projects in environmental and urban upgrading (such as the Tan Hoa – Lo Gom project and the Ho Chi Minh City Urban Upgrading Project).
- Growing awareness that development and management practices must change;
- Growing educational and professional capacity focused on the urban environment;
- Increasing exchange of know-how and cooperation between international and Vietnamese players in the world of urban and environmental development.

However, as this chapter demonstrates, the present practice is also beset with several weaknesses. In the tables below an overview of problems of the present water infrastructure and its underlying societal weaknesses are summarized. A distinction is made between household/neighborhood level (table 8.11) and city/river basin level (table 8.12).

Table 8.11 Water-related infrastructure problems and underlying societal weaknesses at household and neighborhood level in Ho Chi Minh City.

Household and neighborhood level Physical infrastructure problems	Societal weaknesses
▪ Inadequate water supply ▪ Inadequate collection and evacuation of stormwater and wastewater (septic tanks and sewers) which leads to flooding ▪ Water pollution (malodours and insects) ▪ Lack of slope for gravity drainage due to insufficient land heightening ▪ Lack of space for retention basins ▪ Narrow access roads ▪ Lack of green and open spaces ▪ Land scarcity	▪ Low family incomes ▪ High land prices ▪ Insecurity of land tenure ▪ Lack of public funds for infrastructure construction and maintenance ▪ Inadequate local governance with regard to land management, plan implementation and building supervision

The physical infrastructure problems in the two tables are listed on the basis of the analysis given in section 8.3, which has been summarized in table 8.6. Insights of the underlying societal causes have been gained from interviews with involved stakeholders and literature (Lang, 2006; Phu, 2007). The problems of environmental infrastructure are in part a historic legacy. But they have been and still are replicated in new fast-growing residential areas in Ho Chi Minh City, due to inadequate land management, planning and plan implementation. A pressing issue is flooding, which is closely related to the difficulty of drainage of un-heightened low-lying land. Such problems could be avoided, if the city would focus more on controlled building of social housing. Behind this lies a conglomerate of backgrounds: first there is the deficient urban management capacity that is not able to keep pace with urban growth, second there appear qualitative institutional weaknesses which in turn depend on the relative economic and social underdevelopment of Vietnam as a country, third there is a lack of vision and much indecision among the relevant authorities on the way forward in urban development. On the basis of this analysis long-term action plans in four sectors of urban management are proposed in section 8.8.

Table 8.12 Water-related infrastructure problems and underlying societal weaknesses at city and river basin level in Ho Chi Minh City.

City and river basin level Physical infrastructure problems	Societal weaknesses
▪ Increasing water demand ▪ Falling groundwater level ▪ Deteriorating water quality of waterways ▪ Deficient piped distribution systems ▪ Flooding ▪ Deficient drainage systems (diameter and slope too small, leakage, etc) ▪ Inadequate treatment of municipal and industrial wastewater ▪ Inadequate infrastructure for septage collection, treatment and reuse ▪ Uncontrolled reuse of wastewater in aquaculture and agriculture ▪ Lack of development of modern wastewater-reuse options ▪ Uncontrolled urbanization, e.g. on flat and flood-prone land ▪ High demand of relocation housing ▪ Lack of open and green spaces	▪ Fast population growth ▪ Insufficient political emphasis on housing for the low- and middle-income groups ▪ Inadequate land management, planning and plan enforcement due to ill-defined responsibilities, lack of coordination and lack of technical capacity and political strength amongst urban institutions ▪ Inadequate coordination among stakeholders in infrastructure development and environmental protection ▪ Insufficient mobilization of communities and local human resources for infrastructure improvement and environmental protection ▪ Lack of coordinated and adequate urban research and information exchange ▪ Lack of vision on urbanization and infrastructure options

8.8 Long-term sector action plans for environmental infrastructure development

Based on the presented analysis long-term action plans are needed in the sectors of water resources management, sanitation and drainage, social housing and spatial development. These sectors all are characterized by rapidly increasing demand and a backlog of means to meet that demand. Such sector plans would include measures at different levels: the household, the neighborhood, the ward, the district and the city, while there are also strong relationships between the sectors. The development of these action plans should be coordinated by the People’s Committee of Ho Chi Minh City and their implementation at local level requires the leadership of the District People’s Committees. Obviously, they should not contradict the legal requirements of the Socialist Republic of Vietnam.

8.8.1 Action plans water resources management

As shown the need for water in Ho Chi Minh City is rapidly increasing, while there are at present serious quantitative (groundwater) and qualitative (surface water) constraints to meet that increasing need. The problem of long-term water-resources management in the city and a wide area around it has to be approached in an integrated way as proposed by Phu (2007). Action plans would have to address demand management and measures with respect to the use of various sources for various purposes: groundwater, surface water, rain water and treated wastewater at the level of the Dong Nai river basin. The main governmental agencies involved in the development of such plans would be the Departments of Planning and Investment (DPI), Departments of Agriculture and Rural Development (DARD), Departments of Natural Resources and Environment (DONRE) and the People's Committee of the provinces in the Dong Nai river basin. Also the Saigon Water Company (SAWACO) as one of the main stakeholders in water supply would have to play an important part (See annex 8.1). In addition, there is a backlog to provide households with adequate drinking water, which should be overcome by improving and extending the distribution networks of both public and private providers. Action plans in this domain should be worked out primarily at district and ward level.

8.8.2 Action plans sanitation and drainage

The serious problems of flooding and pollution are addressed by several large upgrading projects now running or in preparation (table 8.7). These projects leave the problems of many recently developed unplanned urbanizations unsolved. New projects in the framework of the forthcoming revised Master Plan will have to be proposed and funded. Special attention is needed for adaptation to the impacts of global warming, especially the rising seawater level, which will have strong impacts on Ho Chi Minh City. Measures should be introduced to prevent flooding and enable adequate drainage of stormwater and sewage in existing and future residential zones, either by gravity or by pumping. Concepts of Water Sensitive Urban Design should be studied and introduced in the city (Mitchell, 2006). According to recent adjustment of the Drainage and Sewerage Master Plan of Ho Chi Minh City of 1999 the entire city will have its municipal wastewater treated in twelve large wastewater-treatment plants in the long term (subsection 8.4.2). As the realization of these large treatment plants will take many years, small and medium-sized wastewater-treatment plants will have to be installed in the coming time. Since, however, the present policy concerning these wastewater-treatment plants shows many flaws, this policy should be amended (chapter 9). The issue of wastewater reuse and resource recovery should be put on the political agenda. The operation and maintenance of infrastructure should be put on a more firm financial basis. The main governmental actors in this sector are the Department of Planning and Investment (DPI), the Department of Transportation (DT), The City Flood Prevention Centre and the Department of Natural Resources and Environment (DONRE) of Ho Chi Minh City. The participatory multi-criteria decision making tool developed in this thesis may fulfill a useful function in finding solutions appropriate to different local situations and policy requirements.

8.8.3 Action plans social housing

Inadequate provision of affordable housing to low-income families is a cause of social distress and infrastructure problems. Due to scarce social housing developed in a formal way, in the recent past vast, poorly regulated, residential zones have emerged without satisfactory infrastructure. As government strongly inhibits this form of housing development since 2006, new initiatives in planned housing development for the low income strata are urgently needed. They have to combine a proper response to the housing needs with the lay out of adequate environmental infrastructure. Only in this way expensive upgrading of housing and infrastructure at a later stage can be avoided. In the urban development study for the Ho Chi Minh City Master Plan social housing is proposed to take place in Strategic Development Corridors. These corridors are characterized by a high development potential, and excellent

transport facilities (Urban Planning Institute of Ho Chi Minh City and Nikken Sekkei, 2007, p 5-10). A significant growth of building for the poor will demand stronger governmental initiatives, as market parties up to now have proven to be interested in building for the rich only. Relevant governmental actors besides the People's Committees of the city and the districts are the Department of Construction (DOC), the Department of Natural Resources and Environment (DONRE) and the Urban Planning Institute (UPI).
A continuing big lack of housing for the low- and middle income majority will remain an incentive to unregulated building with its concomitant poor infrastructure and lend it in a sense a certain legitimacy to those who have to deal with it.

8.8.4 Action plans urban environmental development

As any large developing city Ho Chi Minh City is rapidly expanding and facing strongly conflicting land needs. Land prices are invariably extremely high (in the order of 20 mln VND/m^2, 1000 USD/m^2). Up to the present urban construction plans are not able to cope with the speed of development and have several qualitative flaws (Urban Planning Institute of Ho Chi Minh City and Nikken Sekkei, 2007, p 5-8). Land uses other than for transport, commercial buildings and up-market housing until now have received low priority, resulting in a suffocating lack of adequate housing for low and middle income households and green spaces. In an environmental sense the city is becoming unfit to live in. Long-term action plans on spatial development at city and district level are needed. The 2007 study on adjustment of the Ho Chi Minh City Master Plan by UPI and Nikken Sekkei makes a comprehensive proposal for further urban development making a clear distinction between the development on good land (> 2 m above MSL) and bad land (< 2 m above MSL). For new high-potential urban zones the study introduces the concept of the Eco-belt: green, recreational, zones between new road and rail transport corridors and residential zones. The city's low-lying areas must keep their function as flood plains and green zones. Urban development here takes place in the form of clusters: dense urbanization with an area in the order of 250 ha surrounded by natural wetlands (Urban Planning Institute of Ho Chi Minh City and Nikken Sekkei, 2007, p 5-32). The implementation of the concepts of the mentioned UPI Study requires a shared vision among the city's planners and decision-makers and require simultaneous improvements of the policies and practices in land management, planning and plan enforcement. The main governmental players in this field, besides the People's Committee are Department of Planning and Architecture (DPA), the Department of Construction (DOC), the Department of Transportation, the Department of Natural Resources and Environment (DONRE) , the Department of Agriculture and Rural Development (DARD), the Urban Planning Institute (UPI) and the City Flood Prevention Center.

8.8.5 Supportive measures

The effective elaboration of the action plans proposed above in which environmental infrastructure develops within a broader context of people- and environment-friendly urbanization would require the following supporting developments:

- A strengthened political commitment to the execution and enforcement of the indicated plans;
- Improved vertical and horizontal coordination of public, private and community stakeholders;
- Enhanced capacity building and research concerning urban (environmental) management in particular focused on the institutions working at district and ward

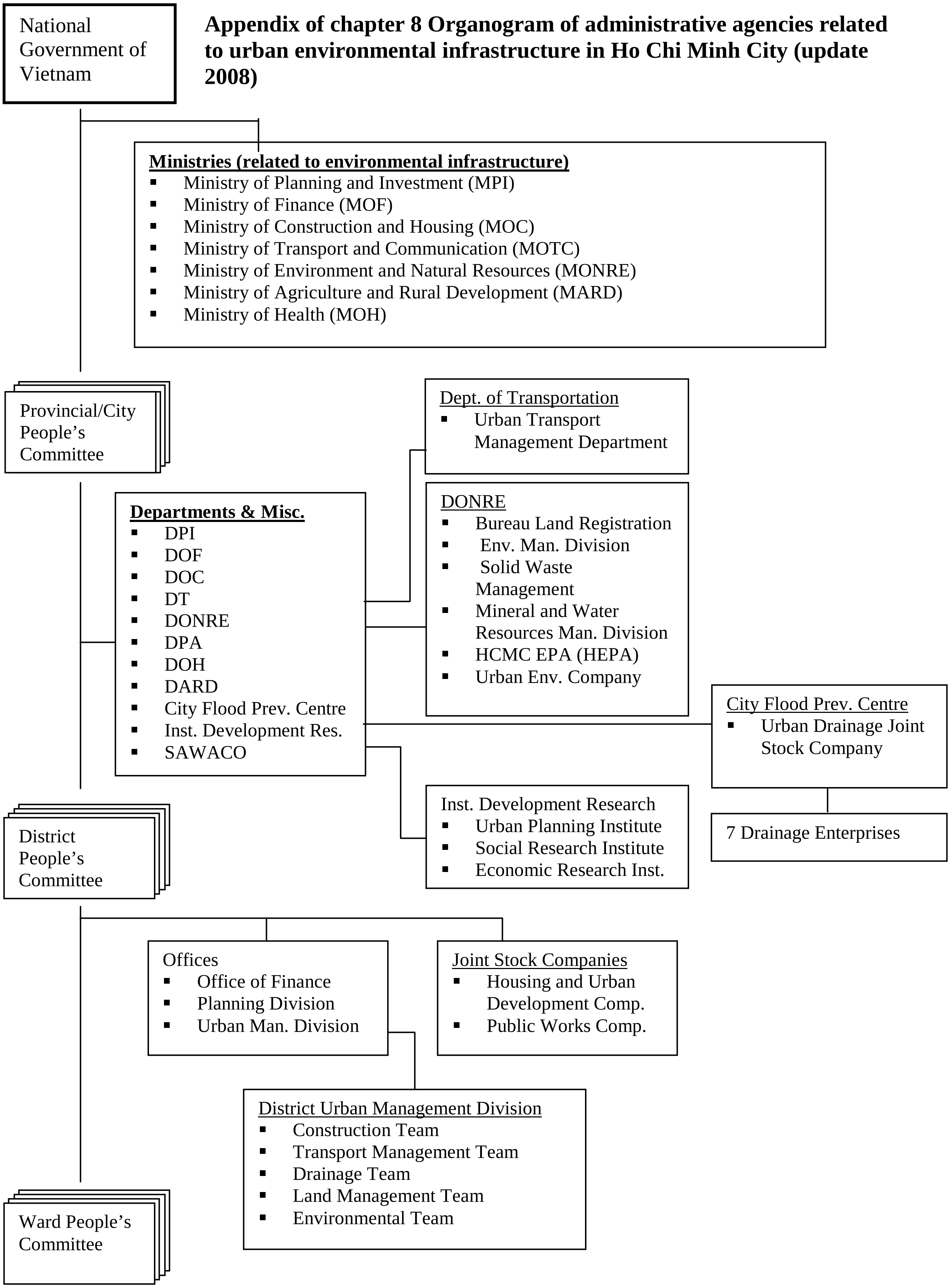
level;

- A consequent empowerment of communities to participate in urban development projects;
- Creation of a firm and transparent financial basis.

8.9 Epilogue

The drainage and sanitation problems of Ho Chi Minh City analyzed in this chapter are a consequence of long time under-investment in this sector and deficient planning and management of urban growth. Presently, the tide is turning and huge projects are underway to upgrade drainage, sewerage and wastewater-treatment infrastructure and to strengthen urban management. Moreover, new projects may now benefit from valuable lessons about community involvement in urban upgrading and new experience is gained day by day. The problem of an urban growth that outpaces planning and plan implementation, however, will remain on the political agendas. Many new initiatives will have to be taken to upgrade neighborhoods realized under a regime of self-construction and to design entire new urban zones. During the elaboration of construction plans for sanitation and drainage infrastructure often the question about the most appropriate drainage and sanitation system for a certain area will be posed. In these cases the multi-criteria learning and decision-making tool SANCHIS elaborated in chapters 3 to 7 of this thesis can be a rational way of reaching decisions. The selection of feasible options and application of the tool in a stakeholder context are presented in chapters 10 and 11.

Appendix of chapter 8 Organogram of administrative agencies related to urban environmental infrastructure in Ho Chi Minh City (update 2008)



CHAPTER 9 AN APPRAISAL OF SMALL-SCALE PUBLIC-COMMERCIAL SEWAGE-TREATMENT PLANTS IN SOUTHERN PROVINCES OF VIETNAM

9.1 Introduction to the policy of small-scale wastewater-treatment plants in Vietnam

Vietnam is industrializing and urbanizing rapidly. In order to combat the expected huge increase of discharge of wastewater, the Vietnamese government started developing a policy to abate water pollution in the 1990s (Khoa, 2006). An important element in this policy is the introduction of industrial and municipal wastewater treatment. The first Vietnamese set of wastewater standards (TCVN 5945-1995, 1995) defined the requirements to industrial effluents (Appendix A.1). This standard was replaced by a more comprehensive set of requirements in 2005 (TCVN 5945-2005, 2005). Effluent requirements for wastewaters of domestic origin were issued for the first time in 2000 (TCVN 6772-2000, 2000). According to these standards the bigger hotels, office buildings, markets and apartment buildings had to be provided with secondary wastewater-treatment plants. For individual households there is the requirement of having a septic tank (subsection 8.3.7), but there are no specified effluent requirements.

The implementation of the aforementioned environmental policy has led to date to a sizeable, but as yet unrecorded, number of small and medium–scale industrial, institutional and residential wastewater-treatment installations. These treatment plants can be considered as a precursor or even a replacement of large scale municipal wastewater-treatment plants. According to the Ho Chi Minh City Environmental Protection Agency (HEPA) 38 - 45% of industrial enterprises that produce wastewater in that province had a wastewater-treatment system by 2005. (Khoa, 2006, p.124). Surveys have shown that the majority of these plants was out of operation or not performing well (Kragic et al., 2005). As many industries and public-commercial establishments discharge untreated wastewater still, it may be expected that many more decentralized treatment plants will be built in the near future. In order to avoid in new plants the deficiencies of the existing plants, it was deemed relevant to analyze the performance and shortcomings of small public-commercial sewage-treatment plants in the framework of this thesis.

On the basis of the outcomes of this analysis (9.2, 9.3), this chapter additionally compares the appropriateness of the different studied treatment technologies and possible adjustments of the Vietnamese policy of decentralized wastewater treatment (9.4).

An evaluation as presented in this chapter has not been carried out in Vietnam until now.

9.2 Research methodology

The evaluation comprised 15 small sewage-treatment plants. The analysis of these plants makes use of the objectives and indicators for wastewater-treatment technologies presented in table 9.1. This list was developed on the basis of objectives and criteria for drainage and sanitation systems detailed in chapter 4 of this thesis.

Table 9.1 Indicators used in the appraisal of wastewater-treatment plants

Objectives	Sub-objectives	Description of indicators
Technical functionality	Compatibility with local infrastructure and physical conditions	Overall performance of treatment plant
	Compliance with local policy framework	Compliance with effluent requirements
	Reliability	Fraction of design capacity utilized Influent organic matter concentration Concentration of mixed liquor suspended solids or excess sludge production Interruption due to faults Built-in technical qualities related to process control
	Flexibility	Adaptability to varying flow-rates and influent concentrations
Protection of health and the environment	Prevention of health impacts to personnel at treatment plant	Labor safety at the plant
	Prevention of emissions to water	Effluent concentrations of pollutants Treatment efficiency
	Prevention of other emissions	Emission of odors, noise and insect vectors,
	Saving and recovery of resources	Reuse of water, nutrients, biogas and biosolids
Social manageability	Low requirements to management capacity of providers	Plant designer's/ plant operators'/ environmental agency's capacity (skills, facilities) to fulfill required tasks
	Stakeholder acceptance	Plant owners' willingness to pay
Economic desirability	Cost-effectiveness	Capital costs Recurrent costs

Information about the treatment plants and their context was gathered by means of structured interviews and one of more visits to the plants. For the interviews a questionnaire was used designed to yield data on the indicators from table 9.1. Topics in the questionnaire were: information about designer, builder, owner and operator of the plant, the drainage system supplying the wastewater, influent and effluent quality, the design, construction and operation and maintenance activities of the treatment plant, the costs of investment and operation and maintenance, and suggested improvements to the plant. The main informers were the designers, builders and the operators. The research team attempted to sample influent, effluent, mixed liquor and stored excess sludge and had the samples analyzed at the laboratory of the Environmental Technology and Management Centre in Ho Chi Minh City. Due to access problems, it was sometimes impossible to sample and analyze the relevant process streams. If possible, additional effluent data obtained from the owner were included. Effluent data of the plants were also requested at DONRE Ho Chi Minh City, but were not accessible. Table 9.2 lists the evaluated sewage-treatment plants.

Table 9.2 The evaluated sewage-treatment plants

	Source of wastewater	Name	Owner and address of plant	WWTP type	Year establish-ment
1	Residential community	Tan Quy Dong	Urban Drainage Company of Ho Chi Minh City, District 7, HCMC	SAF	2001
2	Hospital	Nguyen Trai Hospital	Hospital, District 5, HCMC	Physchem	1998
3		Tropical Hospital	Hospital, 190 Ben Ham Tu, HCMC	SAF/AS	2001
4		Gia Dinh Hospital	Hospital, No Trang Long, Binh Thanh District, HCMC	SAF	2006
5		Nguyen Tri Phuong Hospital	Hospital, 468 Nguyen Trai, District 5, HCMC	Imhoff tank	2000
6		Trieu An Hospital	Hospital District Binh Chanh, HCMC	Imhoff tank	2001
7		Hong Ngu Hospital	Hospital, District Hong Ngu, Dong Thap Province	CMAS	2007
8		Saigon Eye Hospital	Hospital, District Tan Binh, HCMC	SBR-AS	2006
9	Market	Metro An Phu	Market, District 2, HCMC	SAF	2002
10		Agromarket Thu Duc	Joint Stock Housing Company Thu Duc, HCMC	CMAS	2003
11	Office building	Petrovietnam tower	Petrovietnam tower, 1-5 Le Duan, District 1, HCMC	SAF	2007
12	Hotel/resort	New World hotel	New World Hotel, District 1, HCMC	CMAS	2007
13		Anh Duong resort	Anh Duong resort, Phan Thiet, Binh Thuan Province	Surface slow constructed wetland	n.a.
14		Terracotta resort	Bon Mua resort, Mui Ne, Binh Thuan Province	CMAS with pressure filter	2006
15		Canary resort	Canary resort, Mui Ne, Binh Thuan Province	CMAS with pressure filter	2006

Among the 15 plants various treatment technologies are represented: submerged aerated fixed-film reactors (SAF), a physico-chemical treatment plant (Physchem), Imhoff tanks, completely mixed activated sludge (CMAS) plants, a sequencing- batch activated sludge (SB-AS) plant and a surface-flow constructed wetland system (SFCW). This variety of technologies offered an opportunity to compare the appropriateness of different plant types.

9.3 Results

The evaluation of the performance of the 15 sewage-treatment plants focuses consecutively on technical (9.3.1), environmental (9.3.2), social (9.3.3) and financial (9.3.4) aspects.

9.3.1 Technical aspects

Under the heading of technical aspects the study team evaluated the technology choice, design, construction, and maintenance of the plants based on interviews and field observations. The collected data are presented in table 9.3 and the flow-sheets of figure 9.1. The technology in 6 out of 15 plants is the completely mixed activated-sludge process and in 4 plants submerged aerated fixed-film reactors are applied as the main biological treatment step. The Nguyen Tri Phuong (5) and Trieu An (6) hospitals have Imhoff tanks as main treatment step. The Imhoff tank is a primary treatment system aiming at suspended solids removal and digestion, and though it is a very robust primary system, it is inadequate for treatment up to the applicable Vietnamese effluent requirements. The remaining 3 plants of Nguyen Trai Hospital (2), Saigon Eye Hospital (8) and Anh Duong Resort (13) apply respectively physico-chemical treatment, the sequencing-batch activated-sludge process and surface-flow constructed wetlands. In most plants effluent disinfection is conducted by means of dosage of High Test Hypochlorite (calcium hypochlorite) or sodium hypochlorite. In other plants Cl_2-gas dosage (2) and ozonation (8) are applied as disinfection methods.

With the exception of the Tropical Hospital (3) all evaluated treatment plants were said to treat sewage from a separated sewer system pre-treated in septic tanks. As contractors of the treatment plants in several cases (Gia Dinh Hospital (4), Agromarket Thu Duc (10), New World Hotel (12)) stated that they did not have adequate information about the condition and lay out of the existing sewer system, it is highly probable that only a part of the wastewater was collected. As a consequence the installation of treatment plants did not put a complete end to the discharge of untreated wastewater. In Hong Ngu Hospital the sewer system had been thoroughly reconstructed before the installation of the treatment plant.

The design flow-rates of the plants varied between 5 m^3/d (Saigon Eye Hospital (8)) and 1,500 m^3/d (Agromarket Thu Duc (10)). As none of the plants had flow monitoring equipment, it was impossible to say with certainty whether they were working at or near the design flow-rate. According to the operators the plant at Agromarket Thu Duc was severely under-loaded with an actual flow-rate estimated at 400 m^3/d (design: 1,500 m^3/d). The Metro An Phu plant was said to be over-loaded (design: 60 m^3/d; actual load 100 m^3/d). The operators at the Terracotta (14) and the Canary (15) tourist resorts thought that their plants (Q_{design} = 40 m^3/d) were over-loaded during the high season.
In several plants (Tan Quy Dong (1), Tropical Hospital (3), and Nguyen Tri Phuong Hospital (5), the influent was found to be very diluted (COD_{tot} < 100 mg/l) pointing at infiltration of ground or surface water into the sewer system, a high efficiency of septic tanks in the collection sewers, or wrong placement of the influent sampling point. The Tan Quy Dong plant (1) has been taken out of operation, due to massive and irreparable infiltration of river water into the sewers. It was concluded, that the collection of sewage is critical, especially in

complex establishments like hospitals, where buildings are often old and the lay-out of sewer systems is insufficiently mapped. Inadequate collection of sewage reduces the efficacy of the sewage-treatment plant.

Most plants were provided with bar screens and a big equalization/collection tank (HRT of about 1 day) from where the influent is transferred to the treatment units by means of two parallel pumps activated by automatic level switches. The presence of these equalization tanks guarantees flexibility of the plants with respect to variations in flow-rates and organic loads. Since the influent was said to pass septic tanks with a long retention time, strong organic peak loads are unlikely and hydraulic peaks were somewhat dampened. Consequently, the function of the equalization/collection tanks is storage of sewage in case of electricity cuts or double pump failure. Under conditions where such storage is not needed, a simple small pump well with two parallel pumps would suffice. The large equalization tanks allow the use of high-capacity influent pumps without having problems of a very frequent on-off switching. Despite the relatively large capacity of the influent pumps there were complaints about clogging of these pumps in several plants, leading to the need of frequent maintenance. The use of influent pumps with a large capacity could in theory lead to irregular operation, short hydraulic retention times and reduced efficiencies in follow-up processes, such as the sedimentation in Imhoff tanks. The evaluation study was, however, not able to demonstrate the occurrence of this phenomenon.

A common observation at all 15 plants was insufficient monitoring of the sludge accumulation. None of the operators or designers of the 15 plants could report that recently excess sludge had been collected for disposal. No sludge at all was found in the Imhoff tank of Nguyen Tri Phuong Hospital (5), which suggests that this plant is out of operation. In contrast, the Imhoff tank of Trieu An Hospital (6) was overloaded with sludge and badly needed de-sludging.

In none of the 6 activated-sludge plants the usual concentration of activated sludge in the aeration tank of 1 – 6 g TSS/l was found. The measured concentrations were 0.05, 0.25 and 0.44 g TSS/l at the plants of Tropical Hospital (3), New World Hotel (12) and Agromarket Thu Duc (10). At Hong Ngu Hospital (7) and Canary Resort (15) 0.30 and 0.21 g VSS/l was found in the mixed liquor. No sludge was found in excess-sludge storage tanks and operators stated that their plants did not yield excess sludge. The reason of the low sludge concentration in the mixed liquor and the absence of excess sludge could be caused by the low influent BOD_5 and TSS concentrations, high sludge-mineralization rates at the high ambient temperatures of Vietnam, long hydraulic retention times caused by under-loading (Agromarket Thu Duc (10)) and sludge washout from the secondary settlers (New World Hotel (12)). However, interruption of the use or disuse of the plant could lead to the same observation. The measurement of the mixed liquor suspended solids concentration, meant to distinguish between operating and not operating plants, appeared to be inconclusive at this point. A more detailed study of the sludge mass balances and sludge activity would give more insight into causes of the observed low mixed liquor suspended solids concentrations.

In the Tan Quy Dong submerged aerated fixed-film reactor (SAF) plant (1) little sludge attached to the carrier material was observed, probably due to the very diluted influent. In the Metro Anh Phu plant (SAF) (9) a well developed active-sludge mass was found, but no excess sludge production was reported. In the SAF plants of Gia Dinh Hospital (4) and Petrovietnam Building (11) the sludge conditions in the aeration tank could not be verified and the excess-

sludge storage tanks were devoid of sludge. In Gia Dinh Hospital (4) the biological-treatment compartment was not accessible at all without destroying the masonry of the tanks.
The phenomenon of low sludge production deserves more attention. If low or no excess sludge production would be typical for the conditions of Vietnam (high temperature, low influent BOD_5 and TSS), this should be reflected in the design of the plants: the capacity of sludge-dewatering equipment, as built in Hong Ngu Hospital (7) and Agromarket Thu Duc (10) and the size of sludge-storage tanks could be reduced. This could lead to reduction of the construction costs. A more suitable construction was realized in the plants of Saigon Eye Hospital (8) and Metro Anh Phu (9) where the primary settling compartment (septic tank) was assigned as the place for storage of excess sludge.

A lack of sampling points and access ports to tanks appeared to be a shortcoming of several plants (Nguyen Trai Hospital, Gia Dinh Hospital, Saigon Eye Hospital and Terracotta resort). This fact did not only hinder a detailed analysis of the design, but was also a serious drawback in the plant operation. The author had strong doubts about the correctness of the overall design of the plants of Nguyen Trai Hospital (2) and Gia Dinh Hospital (4). It was, however, impossible to draw conclusions, as the processes in the various closed tanks of the plants could not be verified.
Working conditions and labor safety appeared to be acceptable in most plants. However, some improvements would be highly recommendable. Tanks do not always have safe access ladders and railings (e.g. Trieu An Hospital (6), Petrovietnam Tower (11)), so that maintenance activities on the top of these tanks could be dangerous. At the plant in the basement of the Petrovietnam Tower (11) maintenance was severely hindered by lack of lighting, headspace for the operators and fresh air. As a consequence the staff could become increasingly unwilling to operate and maintain the plant.

The maintenance-prone elements of the studied treatment plants were the influent pumps and their float switches, sludge recycling pumps, blowers, compressors and the preparation of hypochlorite solution and its dosage. Blowers and compressors hardly appeared to present maintenance problems. Influent pumps in some cases were reported to get clogged rather often, which could probably be prevented by improved preliminary screening and the application of garbage cutting pumps. In the plant of the Tropical Hospital (3) the sludge recirculation pumps presented frequent problems.
The sequencing batch activated-sludge technology used at the Saigon Eye Hospital (8) needed permanent supervision, as no automated equipment for switching between the various stages of the process was available. The absence of automation may have the advantage of preventing equipment failure, but leads to high costs of manpower. Therefore the manually operated sequencing batch process was judged as inadequate for small treatment plants.
The chemical-disinfection equipment of 4 out of 14 plants was out of operation. This was due to their owners' wish to reduce operational costs and to the idea that disinfection is not useful if the effluent is discharged to a sewer (Metro Anh Phu Market (9) and New World Hotel (12)). Lack of sufficient disinfection at the Terracotta Resort (14) and the Canary Resort (15) was in particular objectionable, as the effluents were discharged onto a bathing beach.The hypochlorite dosing pumps appeared to be a vulnerable part of the technical appliances. As owners and operators in hospitals were keen to keep effluent disinfection running, hypochlorite dosing pumps that were broken down were replaced, or the operator would even revert to manual dosing (Nguyen Tri Phuong Hospital (5)).

The most important conclusions of the technical evaluation of the plants were that the 6 completely mixed activated-sludge plants and 3 out of 4 of the submerged aerated fixed- film reactors were to a high degree ‘textbook’ designs that in principle should able to reach the Vietnamese effluent requirements, provided that the plants be adequately built, operated and maintained. The effluents of the activated-sludge plants at Terracotta (14) and Canary (15) resorts were post-treated by means of a pressure filter. This was motivated by the wish to prevent sludge discharge into the bathing waters. Strong doubts have risen over the designs of the plants of Nguyen Trai Hospital (2) and Gia Dinh Hospital (4). The manually operated sequencing batch activated-sludge technology of Saigon Eye Hospital (8) was judged as less suitable for small treatment plants. Low influent strength, low mixed liquor suspended solids concentrations in the suspended-growth activated-sludge plants, and lack of facilities for process monitoring were the most important critical issues regarding the technical functionality of many plants.

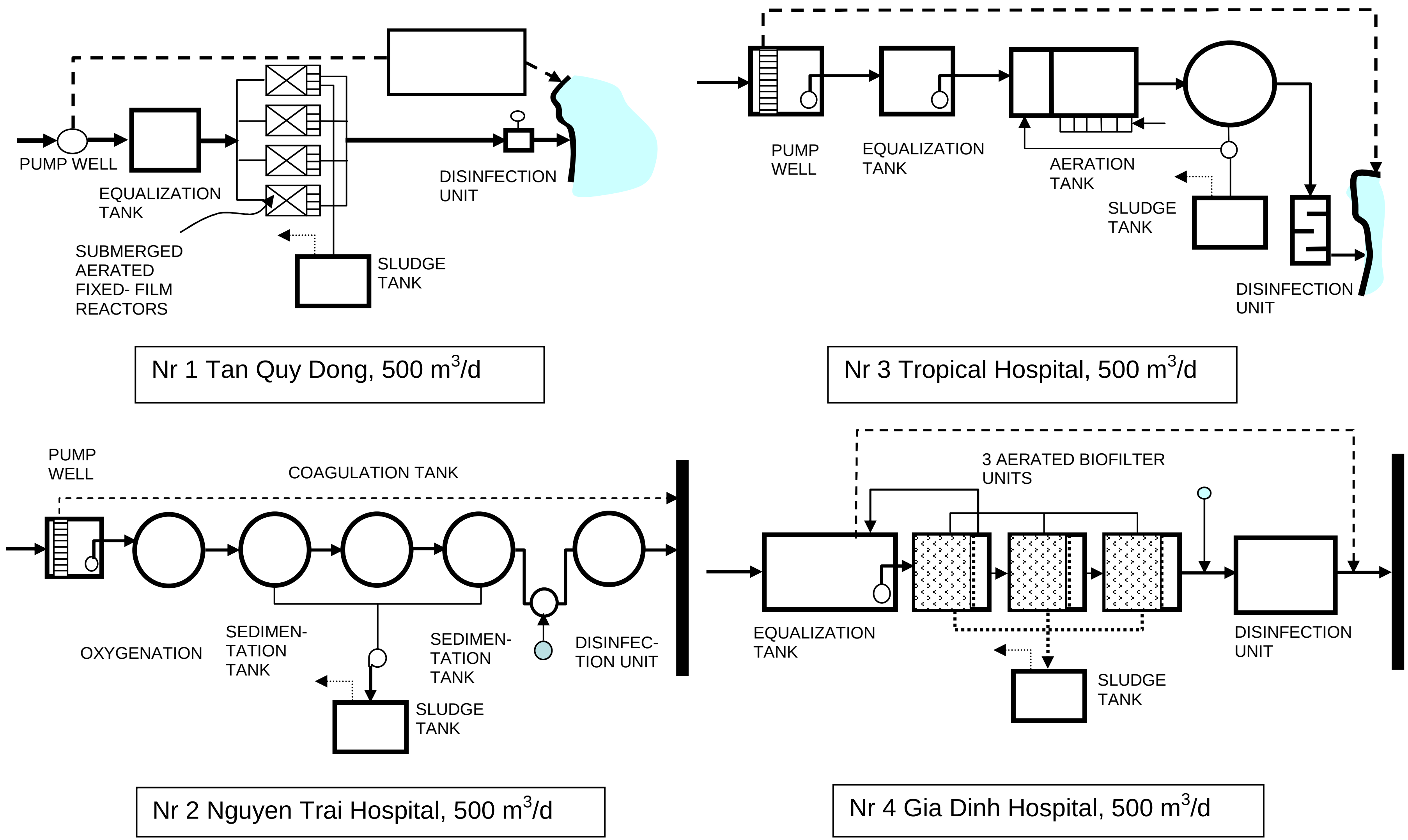
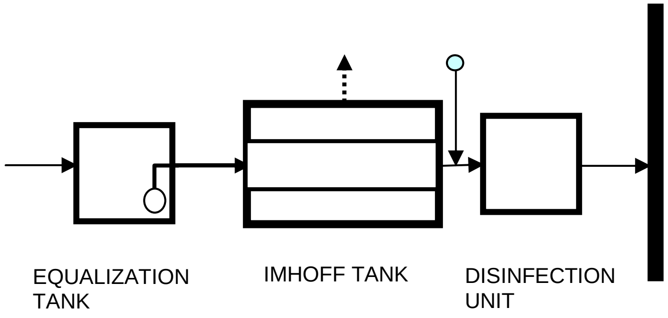
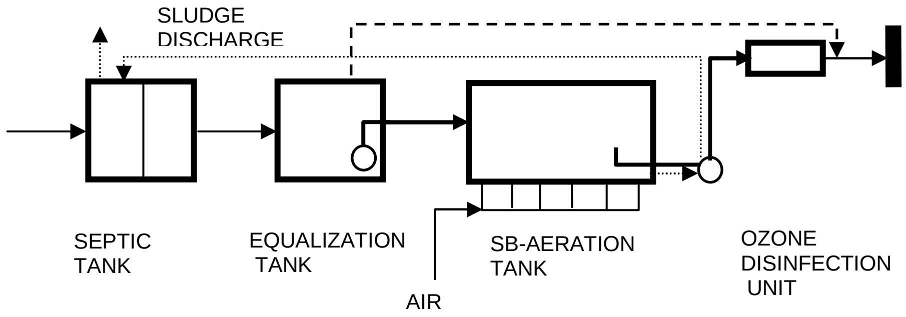


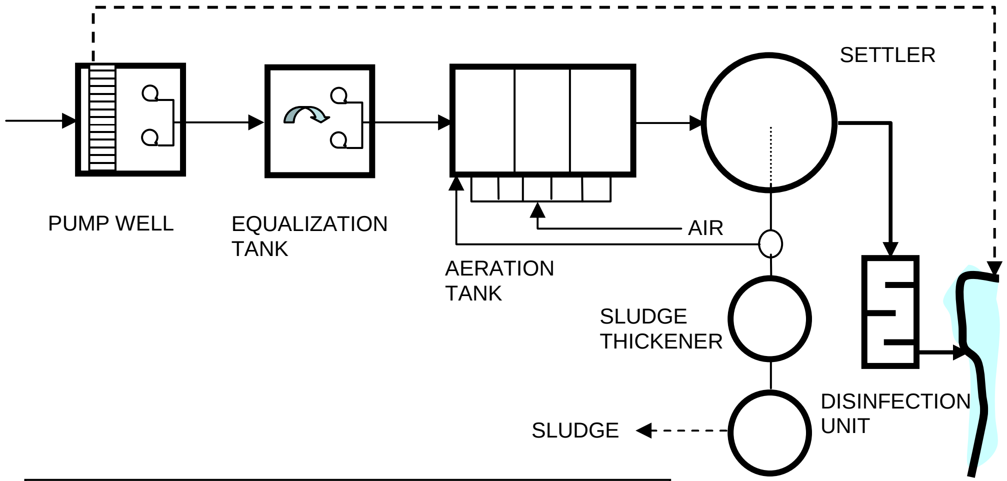
Figure 9.1 Flow-charts of surveyed sewage-treatment plants (1).



Nr 5 Nguyen Tri Phuong Hospital, 200 m^3/d
Nr 6 Trieu An Hospital, 250 m^3/d



Nr 8 Saigon Eye Hospital, 5 m^3/d



Nr 7 Hong Ngu Hospital, 250 m^3/d

Figure 9.1 Flow-charts of surveyed sewage-treatment plants (2).

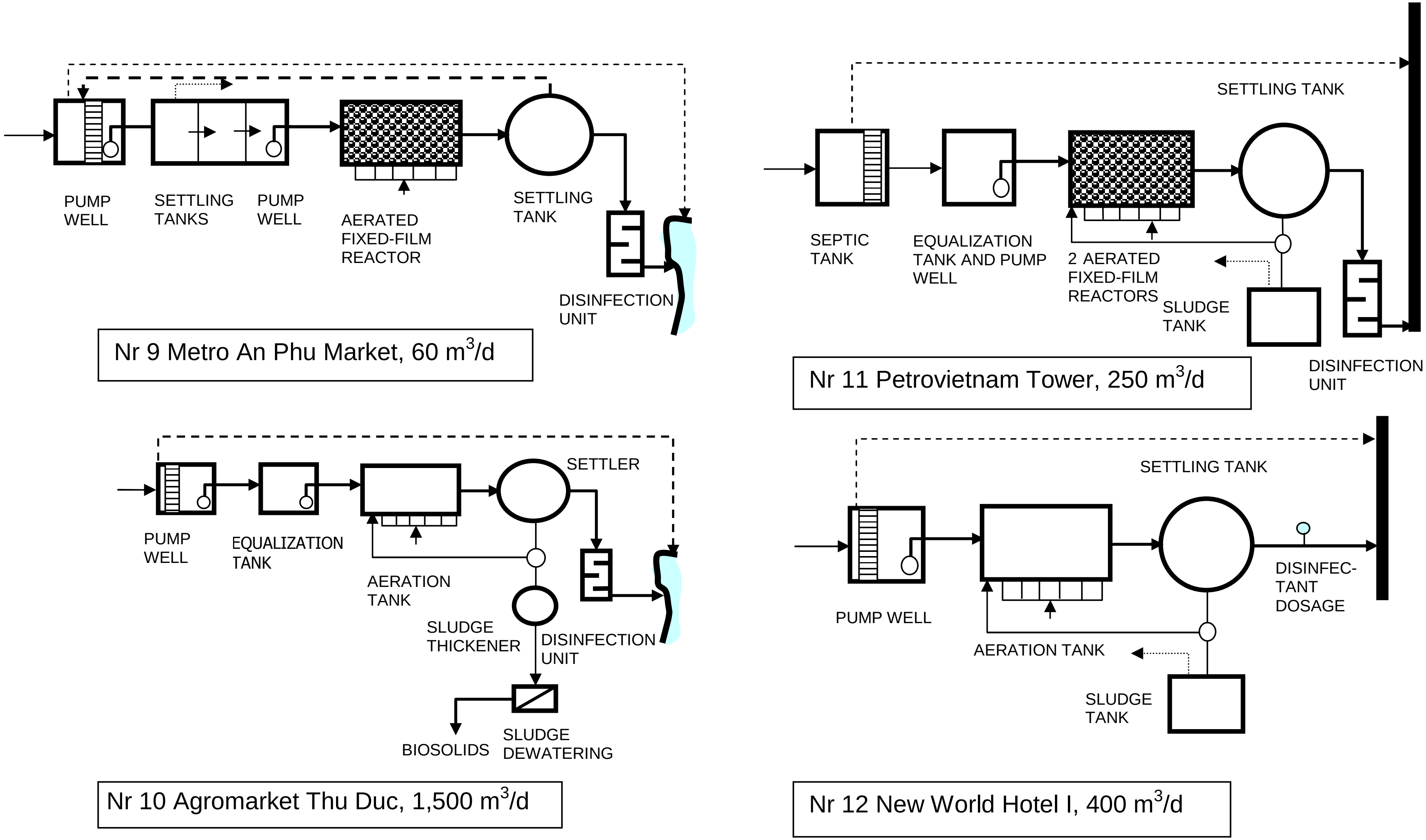


Figure 9.1 Flow-charts of surveyed sewage-treatment plants (3).

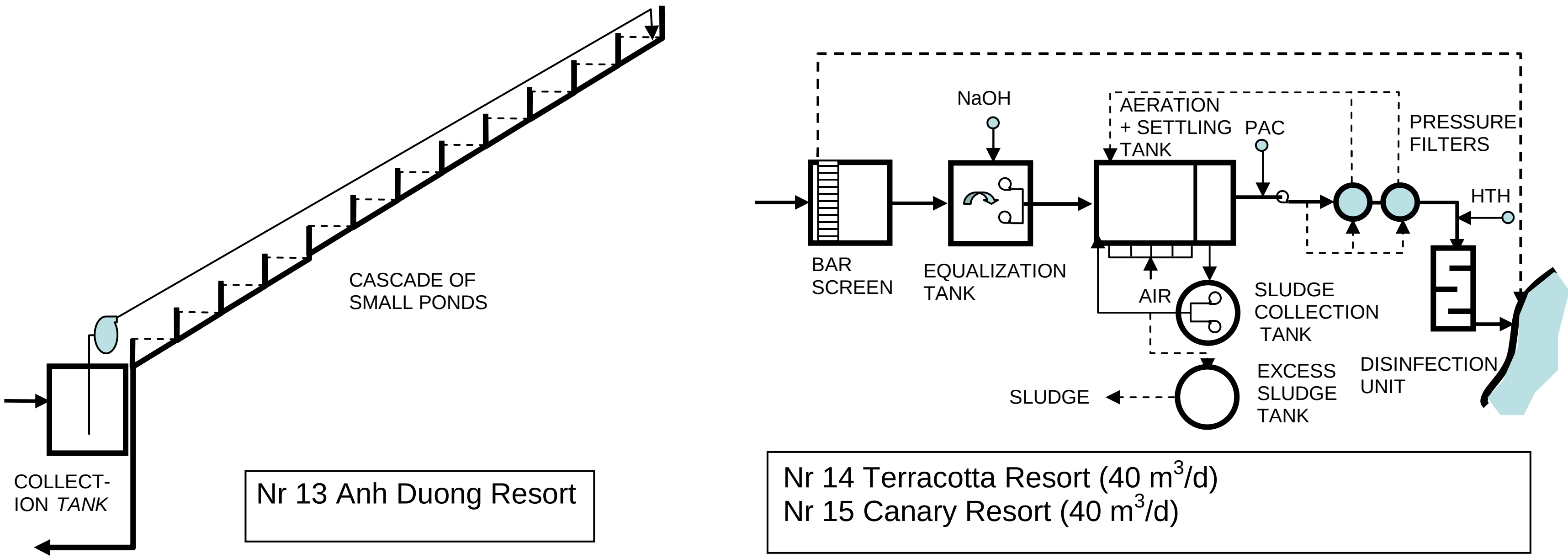


Figure 9.1 Flow-charts of surveyed sewage-treatment plants (4).

Table 9.3. Technical characteristics and operational status of the evaluated treatment plants.

Nr	Name WWTP	Type	Sewer system	Preliminary treatment	Design Flow rate (m^3/d)	Actual DWF (m^3/d)	Land use (m^2)	Volume Aeration tanks (m^3)	HRT_{aer} (hrs)	HRT_{tot} [225] (hrs)	Influent COD_{tot} (mg/l)	MLSS $Conc^n$ (kg TSS/m^3)	Disinfection unit
1	Tan Quy Dong	SAF	Separated	ST + screen	500	500	500	96	5	6	115	Low	HTH, not operated
2	Nguyen Trai Hospital	Phys-chem	Separated	ST	400	500 - 600	300	-	-	2.5	204	n.a	Cl_2-gas, operated
3	Tropical Hospital	AS/ SAF	Combined	ST + mech. screen	500	350	500	250	17	20	72	0.05	HTH, operated
4	Gia Dinh Hospital	SAF	Separated	ST	500	n.a.	250	30	0.7	4	195	-	Cl_2-gas, operated
5	Nguyen Tri Phuong Hosp.	Imhoff	Separated	ST	500	n.a.	Multi-purpose	-	-	n.a.	69; 29; 25	-	HTH, operated
6	Trieu An Hospital	Imhoff	Separated	ST	250	n.a.	250	-	-	n.a.	202	-	HTH, operated
7	Hong Ngu Hospital	AS	Separated	ST	200	n.a.	400	203	24.4	40	n.a.	0.30 (as VSS)	HTH, operated
8	Saigon Eye Hospital	SB-AS	Separated	ST	5	5	10	2.25	5	7	87	low	Ozone, operated
9	Metro An Phu Market	SAF	Separated	ST + screen	60	100	100	16	6	30	529	high	HTH, not operated
10	Agromarket Thu Duc	AS	Separated	Screen	1,500	400	2,000	400	24	> 24	297	0.44	HTH, operated
11	Petrovietnam Tower	SAF	Separated	ST + screen	250	n.a.	214	174	17	40	434	n.a.	n.a.
12	New World Hotel I	AS	Separated	ST	400	n.a.	50	100	3	4	218	0.25	HTH, not operated
13	Anh Duong Resort	SFCW	Separated	ST, grease tank	n.a.	n.a.	360	-	-	n.a.	n.a.	-	Soil infilration
14	Terracotta Resort	AS + F	Separated	ST + screen	40	>40, in season	32	11	7	14	n.a.	n.a.	NaOCl, not operated
15	Canary Resort	AS + F	Separated	ST + screen	40	> 40, in season	32	11	7	14	370	0.21 (as VSS)	NaOCl, not operated

[225] HRT = V/Q_{design}; V = sum of volumes of all process units in the water line, excluding pump wells and equalization tank.

Table 9.4 (1) Environmental performance of sewage-treatment plants 1 until 8.

Nr	Name WWTP	Type	Influent						Effluent							
			COD_{tot} (mg/l)	BOD_5 (mg/l)	SS (mg/l)	N_{tot} (mg/l)	P_{tot} (mg/l)	TC (MPN/ 100ml)	Req[t]	COD_{tot} mg/l)	BOD_5 (mg/l)	SS (mg/l)	N_{tot} (mg/l)	P_{tot} (mg/l)	RC (mg/l)	TC (MPN/ 100 ml)
1	Tan Quy Dong	SAF	115	67	106	51	2.1	n.a.	1995-B	28	16	5	22	0.9	n.a.	n.a.
2	Nguyen Trai Hospital	Physchem	204	191	80	14	n.a.	n.a.	1995-A	40	19	13	n.a.	n.a.	n.a.	n.a.
3	Tropical Hospital	SAF	72	-	13	n.a.	n.a.	n.a..	1995-A	38; 39; 67	15; 29	6; 16; 31	7; 25	n.a.	7; 0.9	<3
4	Gia Dinh Hospital	SAF	195	158	74	88	n.a.	n.a.	1995-A	58	22	7	35	n.a.	15.4	<3
5	Nguyen Tri Phuong Hospital	Imhoff	69; 29; 25	8	7; 7; 10	13; 12;11	n.a.	n.a.	1995-A	76; 29; 9	46	29; 5	12; 6; 10	n.a.	0.12	<3
6	Trieu An Hospital	Imhoff	202	133	39	46	n.a.	n.a.	1995-A	161; 390	16; 174	35; 57	46	n.a.	-	<3
7	Hong Ngu Hospital	AS	n.a	n.a	n.a	n.a	n.a.	n.a.	1995-A	48	36	76	9	6.3	n.a.	2,400
8	Saigon Eye Hospital	SB-AS	87	40	12	33	2.6	n.a.	2000-2	22	12	6	19	2.3	n.a.	3,000
Effluent as per TCVN 5945-1995 A-level (1995-A)										50	20	50	30	4	1	$5 * 10^3$
Effluent as per TCVN 5945-1995 B-level (1995-B)										100	50	100	60	6	2	$1*10^4$
Effluent as per TCVN 5945-2005 A-level (2005-A)										50	30	50	15	4	2	$3*10^3$
Effluent as per TCVN 5945-2005 B-level (2005-B)										80	50	100	30	6	1	$5*10^3$
Effluent as per TCVN 6772 -2000 level 1 and 2 (2000-1/2000-2)										-	30	50	-	6	-	$1*10^3$

Table 9.4 (2) Environmental performance of sewage-treatment plants 9 until 15.
(RC= residual chlorine; TC = total coliforms)

Nr	Name WWTP	Type	Influent						Effluent							
			COD_{tot} (mg/l)	BOD_5 (mg/l)	TSS (mg/l)	N_{tot} (mg/l)	P_{tot} (mg/l)	TC (MPN/ 100 ml)	Req[t]	COD_{tot} (mg/l)	BOD_5 (mg/l)	TSS (mg/l)	N_{tot} (mg/l)	P_{tot} (mg/l)	RC (mg/l)	TC (MPN/ 100 ml)
9	Metro An Phu Market	SAF	529	250	212	72.8	14.5	$1.1*10^6$	1995-B	73; 54	29; 37	46; 14	26	2.1	-	$2.4*10^5$
10	Agromarket Thu Duc	AS	297	141	564	n.a.		n.a.	1995-B	65	28	47	n.a.	n.a.	n.a.	n.a.
11	Petrovietna m Tower	AS	434	210	317	47	4.4	n.a.	2000-1	79	54	21	35	2.9	n.a.	n.a.
12	New World Hotel I	AS	218	84	53	44	7.8	$1.5*10^3$	2000-1	93	75	50	35	5.0	n.a.	$1.1*10^4$
13	Anh Duong Resort	Ponds	n.a	n.a.	n.a	n.a.	n.a.	n.a.	2000-2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
14	Terracotta Resort	AS+F	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2000-2	52	17	n.a.	8	1.1	n.a.	$4.6*10^5$
15	Canary Resort	AS+F	370	229	n.a.	49	13.3	$1.1*10^7$	2000-2	185	99	n.a.	40	9.4	n.a.	$2.4*10^5$
Effluent as per TCVN 5945-1995 A-level (1995-A)										50	20	50	30	4	1	$5 *10^3$
Effluent as per TCVN 5945-1995 B-level (1995-B)										100	50	100	60	6	2	$1*10^4$
Effluent as per TCVN 5945-2005 A-level (2005-A)										50	30	50	15	4	2	$3*10^3$
Effluent as per TCVN 5945-2005 B-level (2005-B)										80	50	100	30	6	1	$5*10^3$
Effluent as per TCVN 6772 -2000 level 1 and 2 (2000-1/2000-2)										-	30	50	-	6	-	$1*10^3$

9.3.2 Environmental aspects

Here, the environmental performance of the 15 small sewage-treatment plants was assessed by measurement of the concentrations of influent and effluent combining these with the judgment of the design and operational status of the plant, since effluent concentrations that comply with the requirements alone are no proof of good functioning of a plant. On the basis of effluent concentrations of COD, BOD_5, TSS and total coliforms compliance with the pertinent effluent requirements was determined. As shown in table 9.4 (1 and 2) the plants had to comply with effluent requirements TCVN 5945-1995 A or B level or TCVN 6772-2000 Level 1 or 2. The quality parameters for which the requirements were not attained are given in table 9.5 (column 4). Given an abnormally low influent strength, several plants produced a sufficient effluent concentration at a low treatment efficiency.

Emissions to air, soil and groundwater of the treatment plants were not taken into consideration, except possible nuisances by odours and insects. Consumption of resources was assessed as element of the recurrent costs (9.3.4). In none of the treatment plants reuse of effluent was practiced.

Criteria for a positive judgment with respect to design and operational status were a sufficient concentration of organic matter in the influent, unit processes that in combination would be capable to reach the effluent requirements, sufficient access to process units for process monitoring and maintenance and uninterrupted operation of the plants. The critical issues concerning design and operational status are mentioned in table 9.5 column 5.

The very low mixed-liquor suspended solids concentration in the suspended-growth activated-sludge plants probably is a site-specific characteristic therefore is not considered as evidence of bad operation. The causes of a low sludge concentration were discussed in subsection 9.3.1. Negative consequences of over-loading could come to expression in their influence on effluent quality, so that overloading is not an independent criterion in the performance assessment. Though under-loading has a negative influence on the costs of treatment per inhabitant or per m^3, this factor is excluded from the valuation of environmental performance.

Table 9.5 (columns 1, 2 and 3) summarizes the judgment of the environmental performance of the plants. Four performance classes are distinguished: sufficient, moderate, insufficient and dubious. The valuation ‘good’ could be given to plants having a good design, operational status and an effluent according to the requirements. In this study none of the 15 studied plants fully satisfied these criteria, so that this performance class has been omitted in table 9.5. The qualification ‘sufficient’ is attributed to plants with a good design and a good operational status, but that did not fully comply with the effluent requirements at the time of the study. The plants of Metro An Phu market (9) and Agromarket Thu Duc (10) were placed in this category. Plants with a ‘moderate’ performance were those that had minor shortcomings in the design and/or the operational status and in addition did not fully reach the effluent requirements. A judgment ‘insufficient’ is attached to plants that have severe shortcomings with respect to their design, operation and/or effluent quality. Finally, the qualification ‘dubious’ was given to plants with a adequate design, but whose performance could not be verified in a sufficient manner. This was the case at Tropical Hospital (3), Hong Ngu Hospital (7) and Anh Duong Resort (13).

Table 9.5 Judgment of the studied sewage-treatment plants based on environmental and technical performance.

Aggregated environmental and technical performance	Nr	Name of plant	Remarks on measured effluent quality	Critical issues concerning design and operational status
(1)	(2)	(3)	(4)	(5)
Sufficient	9	Metro An Phu Supermarket	High total coliform	Overloading; partial clogging of aeration tank
	10	Agromarket Thu Duc	Good	Under-loading
Moderate	11	Petrovietnam Tower	High BOD_5	Process control difficult
	12	New World Hotel I	High BOD_5 and total coliform	Low MLSS concentration; sludge washout from secondary settling tank
	14	Terracotta Resort	High total coliform	Process control difficult; irregular use
	15	Canary Resort	High BOD_5 and total coliform	Irregular use
Insufficient	1	Tan Quy Dong residential area	Good	Massive river water and groundwater inflow
	2	Nguyen Trai Hospital.	Good	Illogical design; no sludge production; process control impossible
	4	Gia Dinh Hospital	Slightly high COD and BOD_5	Process control impossible
	5	Nguyen Tri Phuong Hospital	Slightly high BOD_5	Impossible to reach effluent requirements; no sludge in Imhoff tank
	6	Trieu An Hospital	High COD, BOD_5 and TSS	Impossible to reach effluent requirements; Imhoff tank full of sludge
	8	Saigon Eye Hospital	High total coliform	Very low influent COD Concentration; high manpower requirement
Dubious	3	Tropical Hospital	Good	Very low influent COD concentration
	7	Hong Ngu Hospital	High BOD_5 and TSS	Unknown cause(s) of low treatment efficiency
	13	Anh Duong Resort	N.a.	Hydraulic capacity too small

It may be noted, that design and operational status receive a higher weight in the plant evaluation than the measured effluent quality. This is motivated by the small number of available effluent-quality data, which just produces a snapshot of the environmental performance.

9.3.3 Social aspects

The performance of wastewater-treatment plants depends to a high degree on different forms of support from stakeholders and external incentives, which come to expression in the capacities and willingness to plan, design, build, operate, maintain and monitor the plants. The indicators applied in this study to measure this support and these incentives were the capabilities of designers, contractors and operators, plant owners' willingness to pay and the contribution of environmental agencies to the plants' performance. All evaluated treatment plants had been designed by Vietnamese engineers. Their work was said to be hindered by a lack of data, knowledge and experience, and the tightness of their budgets (e.g. to carry out thorough fact-finding studies before making a design). Vietnamese universities and research centres test wastewater-treatment methods at a lab-scale and those results are disseminated through their engineering students, but there are very few studies at pilot- and demonstration scale whose results would be widely available to practitioners and could serve as a basis for good design[226]. In contrast could the close ties between academic teaching and consultancy in Vietnam be seen as a positive factor in this respect, since field experiences from consultants may easily reach students.

The contractor in principle constructs a plant according to a design approved by the Department of Natural Resource and Environment. Contractors interviewed in this study stated, that the designs of wastewater-treatment plants often lacked detail, were imprecise or even wrong, in their opinion, so that they decided to work according to their own ideas. In this case the constructor takes over a part of the responsibility of the designer and may deviate from a design that has been approved by the authorities. The studied treatment plants looked often, but not always, much less robust and safe than similar plants in Europe. Partly this stemmed from the intention to save money, partly from the space contractors have to deliver substandard work due to inadequate building inspection. Designers and constructors blamed many of the shortcomings of the plants to the owners. Owners are in their eyes responsible for disrepair, lack of funds for operation and maintenance and insufficient training of their operators.

The degree to which a plant's operation was supported by its owner was judged by the support an owner gave his operator(s) to keep the plant running and in good order. An objective indicator of owner support could be the speed with which funds for repairs are allocated in case of technical problems. Several operators said that spare parts (pump rotors and dosing pumps) had to be bought from time to time, but the study team could not ascertain the duration of plant failures. According to operators of wastewater-treatment plants of the tourist resorts their owners assigned them to operate their plants irregularly (or switch them off completely) to save money (Anh Duong (13), Terracotta Resort (14) and Canary Resort (15)). The government's inspection was apparently incapable to correct this behaviour.

The assessment of the training and skills of the plants' operators was based on the way the interviewed operator handled the questions the study team posed about his plant and his own

[226] A very positive exception is the research on baffled septic tanks carried out at CEETIA in Hanoi (Nguyen V. A. et al, 2008).

judgment of his skills to operate the plant. Three types of operators could be distinguished: 1. operators contracted from specialized environmental engineering companies who have treatment-plant service as their main job, 2. specialized operators belonging to the plant owner's organization assigned with plant operation as their main job and 3. operators belonging to the owner's organization with treatment-plant operation as a part-time job. The first two groups were found at Metro An Phu (9), Petrovietnam Tower (11) and Saigon Eye Hospital (8) (contracted company), and at Tan Quy Dong (1) and Agromarket Thu Duc (10) (specialized operators). Large hospitals and the hotels usually have assigned the operation of their treatment plant to their technical staff. In this case skills were less developed, since these persons had several different tasks. Not all operators understood the plant they are responsible for. In some cases this was due to insufficient training, but also lack of motivation may have played a role. It was concluded that maintenance by expert operators could be a decisive factor in the successful operation of a treatment plant, provided design and construction of the plant are correct. The plants of the Metro An Phu Market (9), Agromarket Thu Duc (10) and the Petrovietnam Tower (11) that functioned reasonably well were maintained by staff specialised in environmental engineering. Among the 6 plants that performed insufficiently (table 9.5) 4 lacked expert operators to run the plant (Nguyen Trai Hospital, Gia Dinh Hospital, Nguyen Tri Phuong Hospital and Trieu An Hospital). Employment of expert companies and skilled operators did, however, not in all plants result in sustained good performance, due to other kinds of shortcomings (Tan Quy Dong (1), river water infiltration; Saigon Eye Hospital (8), inadequate design).

Finally, a heavy responsibility for well functioning rests on governmental agencies. With regard to wastewater-treatment plants the involved agencies are the ministries and departments of natural resources and environment (MONRE and DONREs) and construction (MOC and DOCs). For hospitals the ministry and departments of health (MOH and DOHs) also play a role. Their present tasks are framing the policy to establish wastewater-treatment plants and the effluent requirements, the approval of designs, certification of completed installations and the monitoring and inspection of the operation of the plants.

As opposed to the other stakeholders the environmental agencies were not addressed directly to ask about their share in the management of the sewage-treatment plants, but their performance could be derived in an indirect way. The fact that several of the evaluated plants functioned insufficiently pointed at inadequacies of their work.

The causes of these inadequacies could be summarized as (1) lack of consensus and cooperation between state and industry (in this case between state and the public commercial enterprises), (2) severe understaffing, financial constraints, poor management and insufficient supervision and monitoring, and (3) the inexistence of stable and long-term environmental strategies (Khoa, 2006, p 170). In a follow-up stage of this evaluation study it would be important to work with environmental agencies to strengthen their capacity to support the policy of decentralized treatment plants. In his evaluation of the policy regarding end-of-pipe treatment of industrial enterprises Khoa (2006, p 169) notes that public pressure, e.g. complaints by residents in the surroundings of polluting industries, effectively motivates and enhances the environmental enforcement of authorities. In this study evidence of such public pressure was found in the case of Hong Ngu Hospital (7). Absence of complaints could be explained by the fact that the pollution of most public-commercial establishments was imperceptible to the public, save perhaps in the case of the tourist resorts. This implies that the enforcement of government policy in the case of public-commercial sewage-treatment plants often misses this external driver, which could lead to a lax attitude with respect to the adequate operation of the plants and consequently frequent under-performance.

9.3.4 Financial aspects

Cost-effectiveness is an important requirement to be put to treatment plants. It was evaluated by analysing investment (9.3.4.1) and recurrent costs (9.3.4.2) of the evaluated plants. An overview of the gathered financial data is given in table 9.7. In 9.3.4.3 the overall costs are presented and compared with the reported costs of small *industrial* wastewater treatment plants and large-scale municipal wastewater-treatment plants in Vietnam.

9.3.4.1 Investment costs

Figure 9.2 shows the investment costs, expressed in US dollars in the year of construction, as function of the treatment-plant capacity[227]. All plants were built in the period 2001 to 2007. In the range of 5 – 1,500 m^3/d a proportional relationship between investment costs (C_i, USD) and design capacity Q (m^3/d) was found which was best expressed by the linear equation:

$$C_{inv} = 202.3 * Q + 1866 \qquad (9.1)$$

This means that a capacity increase of 100 m^3/d would cost approximately 20,300 USD. In Vietnam in the period 2001 - 2007 a plant with a capacity of 500 m^3/d cost about 100,000 USD on average.
On the basis of the available data no significant difference between the activated sludge (6 plants) and the submerged aerated fixed film reactor plants (5 plants) could be found. The proportional relationship between flow-rate and investment costs is remarkable, since the logic of construction and several literature sources ((Loetscher, 1999); (Qasim, 1999) indicate diseconomies of small scale, according to which the construction costs of small installations are higher per unit of capacity. In fact, the investment costs of the smallest installation in this study, Saigon Eye Hospital (8)(5 m^3/d, 6,000 USD), had been significantly higher than would be expected on the basis of the above-mentioned equation (2,900 USD). Accordingly, it may be expected that for plants smaller than 40 m^3/d a capacity-costs relationship holds that is different from the linear one given above, but the available data do not suffice to reveal that relationship.
The proportional relationship in the range between approximately 40 and 1,500 m^3/d could be ascribed to extra components, and thus additional expenses, required in the construction of a relatively large plant, such as the plant of the Agromarket Thu Duc (10) (1,500 m^3/d), that are usually not required for smaller plants, such as service buildings, access roads, fences and on-site sludge-treatment devices. Comparison with international figures shows that the costs of a 1,500 m^3/d activated-sludge plant in Vietnam (320,000 USD (2003)) is in the order of 12 % of the costs of such a plant in the Europe (2 million Euro/2.7 million USD)[228].

[227] Actualization of the investment costs to the same year was not applied, since there is too much uncertainty about price indices of wastewater-treatment plant costs for a reliable actualization.
[228] Investment costs of activated-sludge plant of 1,500 m^3/d is 200 Euro/PE. 1 PE = 0.15 m3/d (after Geenens and Thoeye (2000)).

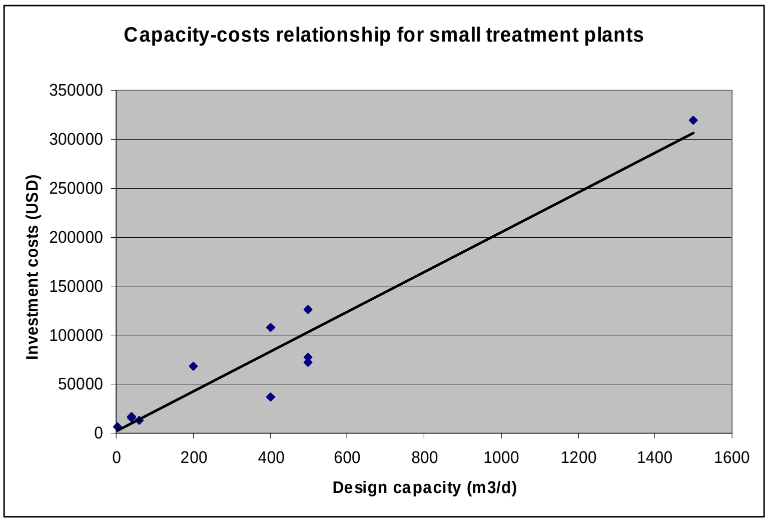


Figure 9.2 Investment costs as function of design capacity for small wastewater treatment plants in Ho Chi Minh City and surroundings (construction period: 2001 – 2007).

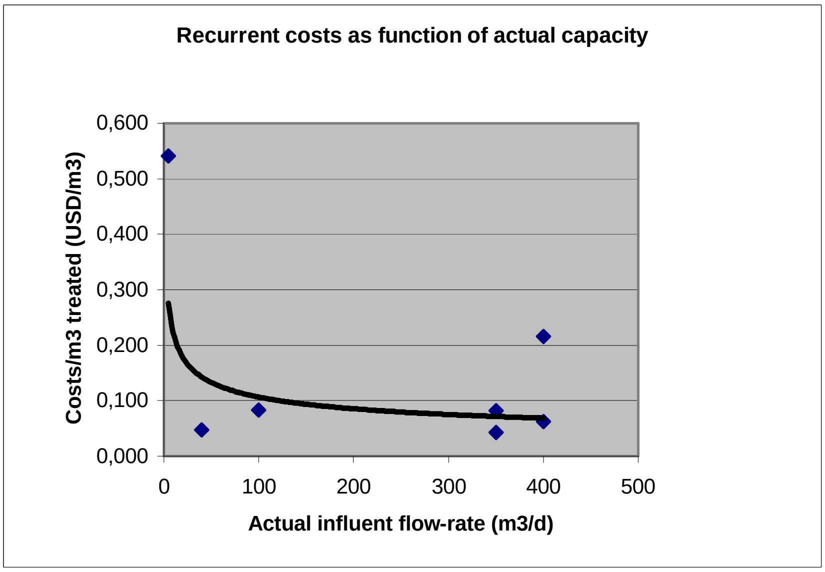


Figure 9.3 Recurrent costs as function of actual influent flow-rate for 7 small wastewater-treatment plants in Ho Chi Minh City and surroundings (2007).

Table 9.7 Financial data of the evaluated sewage-treatment plants.

Nr	Name WWTP	Type	Year of construc-tion	Design Flow-Rate (m^3/d)	Actual Flow-rate (m^3/d)	Investment (mln VND)	Investment (USD)	Recurrent Costs Resources (mln VND/m)	Recurrent Costs Manpower (mln VND/m)	Total Recurrent costs (mln VND/m)	Recurrent costs/m^3 treated (VND/m^3)/ (USD/m^3)[229]
1	Tan Quy Dong	SAF	2001	500	350[230]	1,900	126,000	8.8	5	13.8[231]	1,300 / 0.08
2	Nguyen Trai Hospital	Phys-chem	1998	400	600	1,500	108,000	4.5	n.a.	n.a.	n.a.
3	Tropical H.	SAF/AS	2002	500	350	1,200	77,900	6.7	0.5	7.2	690/ 0.043
4	Gia Dinh H.	SAF	2006	500	n.a.	1,164	72,800	n.a	n.a	n.a.	n.a.
5	Nguyen Tri Phuong	Imhoff	2000	500	n.a.	n.a.	n.a.	3.5	0.3	3.8	n.a.
6	Trieu An H.	Imhoff	2001	250	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
7	Hong Ngu H.	AS	2006	200	200	1,100	69,000	n.a.	n.a.	n.a.	n.a.
8	Saigon Eye H.	SBR-AS	2006	5	5	96	6,000	0.3	1.0	1.3	8,670 / 0.54
9	Metro An Phu	SAF	2002	60	100	200	13,000	3.7	0.3	4.0	1,330 / 0.08
10	Agromarket Thu Duc	AS	2003	1,500	400	5,000	319,600	36	7.0	42	3,460 / 0.22
11	Petrovietnam Tower	SAF	2007	250	n.a.	n.a.	n.a.	n.a	n.a	n.a.	n.a.
12	New World Hotel I	AS	2007	400	400	596	37,500			12	1,000 / 0.06
13	Anh Duong Resort	Ponds	n.a.	n.a.	n.a.	n.a.	n.a	n.a	n.a.	n.a.	n.a.
14	Terracotta Resort	AS + F	2006	40	40	275	17,300	n.a.	n.a.	n.a.	n.a.
15	Canary Resort	AS + F	2006	40	40	250	15,700	0.8	0.1	0.9	750/ 0.05

[229] 1 USD = 16,000 VND (2007).
[230] The Tan Quy Dong plant has been stopped (2007).
[231] Data from 2004.

9.3.4.2 Recurrent costs

The recurrent costs of the sewage-treatment plants are subdivided into costs of regular inputs (electricity, chemicals, quality analysis, sludge removal, repairs) and manpower. The recurrent costs/m^3 treated could be calculated for 7 out of 15 plants. These data are graphically represented in figure 9.3.

The recurrent costs per m^3 treated vary considerably not only for plants with different flow-rate, which could be expected, but also for plants with more or less the same flow-rate. At a rate of 350 - 400 m^3/d (Tan Quy Dong (1), Tropical Hospital (3), New World Hotel I (12)) the recurrent costs are in the order of 1,000 VND/m^3 (0.062 USD/m^3). The high costs at Agromarket Thu Duc (10) (400 m^3/d, C_r = 0.21 USD/m^3) were due to the fact that this plant has a design capacity of 1,500 m^3/d and was run at 400 m^3/d (in 2006). The high costs at Saigon Eye Hospital (8) (5 m^3/d, C_r = 0.54 USD/m^3) can be explained by the relatively high costs of surveillance of this small plant. The best-fitting power trendline for the recurrent costs (C_r , USD/m^3) as function of design flow-rate (Q, m^3/d) found on the basis of the data shown is:

$$C_r = 0.46*Q^{-0.32} \quad (9.2)$$

It should be noted that cost values based on equation 9.2 have an indicative character, since there were significant uncertainties in the values of the costs and actual flow-rates from which this equation was derived.

9.3.4.3 Overall costs of small sewage treatment plants

The investment and recurrent cost ranges (operation and maintenance) of the small sewage-treatment plants with design flow-rates between 40 and 400 m^3/d are 94 to 432 USD/m^3/d and 0.042 to 0.081 USD/m^3 respectively (table 9.8). On the basis of an assumed design life-time of the plants of 10 years and a MARR value of 5% a total treatment cost (USD/$m^3_{treated}$) was calculated.

Table 9.8 Costs of small sewage-treatment plants in Ho Chi Minh City, Vietnam, in 2007 (flow-rates: 40 – 500 m^3/d).

Type of wastewater	Effluent requirement	Investment costs (USD/m^3/d design capacity)	Recurrent costs (USD/m^3 treated)	Total costs (USD/m^3 treated)
Domestic wastewater pre-treated in septic tanks	TCVN 5945-1995-A and B, TCVN 6772-2000 level 1 and 2	94 – 432	0.042 – 0.081	0.10 – 0.19

For the plants with a design flow rate between 40 and 500 m^3/d the total costs including depreciation of the equipment, interest payment and recurrent costs ranged from 0.10 to 0.18 USD/m^3 treated. The treatment at the plant at Saigon Eye Hospital (8) (5 m^3/d) was expensive (0.96 USD/$m^3_{treated}$), due to the small flow-rate and relatively high investment and operation costs. It should be noted that several of the plants whose costs are assessed here do not perform well, which is partly due to an insufficient operation and maintenance effort. A plant

whose performance is judged as sufficient and that could be costed, namely the Metro Anh Phu plant (9), had total exploitation costs of 0.12 USD/$m^3_{treated}$. At Metro Anh Phu the costs would be 0.21 USD/$m^3_{treated}$, if the plant would be operating at its design capacity of 60 m^3/d instead of its actual 100 m^3/d. At Agromarket Thu Duc (10) the exploitation costs per m^3 treated could be significantly reduced if the plant would be working at its design capacity of 1,500 m^3/d.
The exploitation costs of the sewage-treatment plants reported here were considerably lower than the costs of small-scale industrial wastewater-treatment plants Khoa has presented in his thesis (Khoa, 2006). This could be explained by the lower organic loading rate of the former.
High treatment costs were reported as a main motive to switch off and/or neglect wastewater-treatment plants at small enterprises (Khoa, 2006, p 171). Calculation of the treatment costs per room and per day at Canary resort (45 rooms) showed that the overall treatment costs were 0.48 USD/room.day under the rather unfavourable assumptions of a plant design life time of 10 years, a MARR of 10% and a room occupancy of 40%. Given room rates in the range of 20 - 60 USD/day, this amount does hardly seem a sufficient reason for resort owners to switch off their treatment plants. Nevertheless the argument of high costs is also used in the public-commercial sector for switching off sewage-treatment plants.

9.3.5 Deficiencies of small public-commercial sewage-treatment plants

On the basis for the analysis presented in the previous subsections, table 9.9 summarizes the main critical issues related to small sewage-treatment plants, the phases in which they have their deepest impact and the most responsible actors. The overall picture is one of a multitude of small and a few influential deficiencies. The findings reported in this table are the basis for the recommendations given in section 9.5.

How do the results of this appraisal compare with earlier studies in Vietnam and abroad?
In a study on decentralized industrial wastewater-treatment plants in Ho Chi Minh City and surroundings Krajic et al. (2005) reported that out of 190 companies that discharge wastewater, 124 had a treatment plant of which 103 were operable, or in operation, and at least 21 were not in operation. Khoa (2006, p 125) concluded, though not with complete certainty, that 4 out of a group of 15 industrial small plants were out of operation or not functioning well. These earlier studies in Vietnam do not give details of the malfunctioning of plants, but Khoa (2006, p 132) states that decentralized plants at small enterprises often show failures, are out of operation or only switched on during visits of environmental authorities. He mentions as causes of deficient functioning: insufficient financial capacity, knowledge and environmental awareness of plant owners and inadequate enforcement of regulations by the responsible government agencies. The latter shortcoming is partly due to the large number of small plants to be supervised. The results of the present study on small public-commercial plants correspond to a high degree with those of Krajic et al (2005) and Khoa (2006), which is not surprising as both categories function under the same institutional conditions.

Table 9.9 Summary of critical issues related to plant malfunctioning as per phases and responsible actors.

Phase	Critical issues related to malfunctioning of treatment plants	Responsible actor
Technology choice, design and construction	Insufficient pre-design fact finding Inadequate technological design Insufficient monitoring facilities Inadequate built-in labor safety	Designer
	Inadequate match between sewage collection and treatment system resulting in under- and over-loading	Designer and Owner
	Absence of adequate guidelines for design and effluent quality Inadequate inspection of designs and new plants	Government Agencies
Construction	Use of low-quality equipment and construction material	Contractor
Operation and Maintenance	Irregular operation of all process units of a plant Neglect and disrepair of equipment Low treatment efficiency Irregular de-sludging Inadequate protection against corrosion Insufficient operator training, skills and tools	Owner
	Lack of understanding of plant	Operator
	Inadequate and infrequent inspection regime	Government Agencies

Very few international publications about trouble-shooting studies in small sewage-treatment plants were found: one for Greece (Tsagarakis et al., 2000) and one for England (Rowland and Strongman, 2000). The conditions in these studies were different from the situation in Vietnam as the researched plants were publicly owned and managed. In Greece, however, a high percentage of plants at that time had failed (13 out of 147) or had never come into operation (63 out of 147) which the authors blamed on a fragmented institutional set-up and inadequate project and fund management. In the British study the focus was on learning from technical deficiencies. The efforts to improve performance there were directed towards centralization (less plants), taking away causes of faults, and reliable automation and telematics. It is evident from the various studies that the management of many small plants is a laborious task that puts special demands to governmental agencies.

9.4 Are some technologies more appropriate than others?

It was argued above that adequate institutional support is a crucial aspect in the efficient performance of wastewater-treatment plants (9.3.3). However frequent technical problems and high operation and maintenance costs of an - apparently inappropriate -technology could discourage stakeholders to persist in maintaining and operating a plant with failure as a result. It can be inferred therefore that the choice of appropriate technologies should not be ignored. Sasse (1998) points out that, due to inadequate surveillance and a need to keep costs low, critical requirements to decentralized treatment systems (1-500 m^3/d) in developing countries are low maintenance needs, robustness, independence of technical energy and the use of local skills for construction and supervision. As a consequence he stresses the need of low-tech *non-switch-off-able* systems: simple anaerobic and natural aerobic treatment systems like septic tanks, anaerobic upflow filters, Imhoff tanks, stabilization ponds and constructed wetlands. The operation of these systems is simple and they can not be switched off when their owners want to save money. In addition, Lettinga (2006) and Van Lier and Lettinga (1999) recommend for tropical developing countries high-rate anaerobic pre-treatment methods (especially UASB reactors) combined with aerobic post-treatment (ponds and soil infiltration). Wilderer and Schreff (2000) point at the low effluent quality of low-tech sewage-treatment methods and stipulate the need of high-rate automated compact plants. An example of such small compact plants are certain Japanese 'Johkasou' systems (Yang et al., 2001), which in fact have been proposed in the Master Plan of Ho Chi Minh City for areas with a population density less than 200 per hectare. Apparently, various authors recommend strongly different technologies as appropriate, which may be due to their different images of the conditions in which these technologies have to perform. To answer the question of appropriateness it would be necessary to prove that some technologies perform significantly better in the situation of Ho Chi Minh City than others, and at the same to indicate the characteristics responsible for that better performance.

As can be inferred from table 9.2, for 12 out of 15 plants a mechanized technology had been selected, for two Imhoff tanks were used (Nguyen Tru Phuong (5) and Trieu An (6) Hospitals) and for one surface-flow constructed wetland technology (Anh Duong (13)). Apparently lack of space (high building density) had in all but one case determined the choice. All designs appeared to be adapted to Vietnamese conditions by measures to reduce construction costs and the use of simple manual equipment to control the mechanized plants. However, the wish to limit costs had in some cases gone at the expense of the quality of the construction (rapid corrosion, inadequate labor safety) and the ease of maintenance.
The appraisal demonstrated no correlation between absence of mechanization and adequate performance. The plants that were judged 'sufficient' or 'moderate' were all mechanized plants (table 9.5). They were suspended-growth activated sludge plants and submerged fixed-film reactors. The two Imhoff tanks did not function properly and the performance of the surface-flow constructed wetland could not be verified.
It is evident, that in particular the number of non-mechanized technologies in the present study was far too limited to draw conclusions about the enhanced appropriateness of *non-switch-offable* technologies. As, however simple non-mechanized technologies like Imhoff tanks (this study) and septic tanks (Harada et al., 2007) have shown to function insufficiently, due to design flaws and insufficient care, and in several cases mechanized plants showed an acceptable, though not perfect, performance, the social circumstance of adequate design and operation and maintenance seemed more important to proper performance than the absence of mechanized equipment.
An important observation was the low biomass concentration in the aeration tank in suspended-growth activated-sludge plants, while at least in the Metro An Phu plant (9) the carrier material was well covered with biomass. A high degree of sludge retention is imperative under the given conditions of low influent dissolved and particulate organic matter concentrations and the concomitant reduced sludge growth- rate. In this respect the attached-growth systems performed much better than the suspended-growth systems and accordingly were judged as more appropriate (subsection 6.5.4.3).

9.5 Recommendations for improvement of decentralized wastewater treatment

In addition to learning lessons from the weaknesses of treatment plants, the question is posed about the need of adjustment of the prevailing Vietnamese policy of community on-site sewage treatment? There seem to be two main ways to proceed: either to improve the present decentralized practice, or to choose for more centralization. It may be assumed that in large-scale treatment plants the risk of failure is smaller than in small-scale plants, while the costs per m^3 treated are lower (chapter 7). In highly developed urban and seaside tourist areas where centralized treatment is going to be established within about five years, it is hardly worthwhile to continue to demand individual secondary wastewater-treatment plants with their apparent high risk of failure. An exception is the treatment of hospital wastewater which may present an immediate health risk if not properly disinfected. In many other areas the choice for a centralized approach would probably mean the continuation of untreated discharges for many years, since the institutional environment and funds for larger-scale sewer and wastewater-treatment systems are lacking. According to the author's opinion, the policy as reflected in TCVN 6772-2000 should be continued here, but the regulations and the practice should be strongly improved.

Some recommendations for this improvement are given here (table 9.10). They are the author's view and not necessarily shared by Vietnamese stakeholders in wastewater treatment. The measures are directed towards respectively designers and construction companies, plant owners and governmental agencies. Although most of the recommended measures seem obvious in the light of the preceding observations and do not need further detail, some are explained.

This study showed several cases where severe problems occurred with the collection of the wastewater. Therefore it is recommended that designers address collection and treatment in an integrated way based on a thorough analysis of the local conditions. With respect to the Vietnamese effluent requirements should be noted, that these take insufficiently into account 1) the treatment efficiencies attainable as function of wastewater-treatment technologies and 2) the effluent disposal conditions. An example is the requirements for nitrogen compounds. The Vietnamese effluent standard TCVN 5945-2005 B requires maximum concentrations of 10 mg/l NH_4-N and 30 mg/l total nitrogen (N_{tot}). If the N_{tot} concentration of the influent would be less than about 40 mg/l and the N_{tot} removal would be 25% (table 6.5.5), these effluent concentrations are attainable by a nitrifying activated-sludge process. But if the influent contains more than 40 mg/l N_{tot} , most of it in the form of ammonia, de-nitrification would be indispensable to attain a N_{tot} concentration of 30 mg/l.

Table 9.10 Recommendations for improvement of small sewage-treatment plant practice in Vietnam.

Phase	Recommended measures
Technology choice, design and construction	Detailed analysis of sewage collection systems and integrated design/construction of collection and treatment systems Use of internationally accepted design and construction standards Provision of monitoring facilities for flows, process water and sludge Analysis of excess sludge generation and adaptation if needed an adaptation of design guidelines Improved labour safety Improved durability of equipment (pumps) and construction (corrosion prevention, increased design lifetime) Reduction of maintenance requirements Preparation of high-quality operation manuals
Operation and Maintenance	Employing expert personnel for operation and maintenance Regular operation of all process units of a plant Timely maintenance and repair of equipment
Governmental regulations, research and enforcement	Adjustment of effluent requirements to the needs and possibilities of decentralized treatment Public research about adaptation of technologies to Vietnam-specific conditions Issuing of national guidelines for small wastewater- treatment plant design and construction, including collection systems Requiring a diploma for wastewater-treatment plant operators Improvement of sector-specific inspection regime Sector-specific (hotels, residential areas) awareness-raising among prospective owners of treatment plants and increased cooperation between owners and governmental agencies

This would add much to the cost without much environmental benefit in the case of small treatment plants. Effluent requirements therefore should be a function of the capacity of the treatment facility. In the case of the TCVN 6772-2000 no requirement for N_{tot} is set, but only for nitrate (30 mg/l). In practice this means that ammonia (NH_4^+ -N) could be discharged at any concentration, and that nitrification of domestic sewage, which is good for the protection of the oxygen regime of surface waters, is discouraged. Ineffective requirements, such as these, lead to lack of confidence among the stakeholders involved in wastewater treatment.

As apparently several of the analysed plants were beset with unnecessary deficiencies, it is proposed here to carry out research aiming at small sewage-treatment plants appropriate to Vietnamese urban conditions. Guidelines for the Vietnamese design practice should be issued on the basis of the results of such local studies and international experiences. This would probably lead to better treatment plants. It is suggested further that a sector-specific (hotels, residential projects, etc) governmental approach, involving organizations that are trusted by owners and managers of public-commercial establishments, could lead to a higher environmental ambition level among prospective owners.

9.6 Conclusions

An evaluation of 15 small-scale sewage-treatment plants in the range of 5 to 1,500 m^3/d in the Southern provinces of Vietnam demonstrated that only 6 showed an acceptable performance in terms of organic matter removal and operational status (table 9.5). The various observed weaknesses could be ordered according to the design, construction and operation of the plants and according to responsible actors (table 9.9). Salient findings were inadequate designs, the impossibility of process monitoring in some plants and the near absence of sludge in the aeration compartments of suspended-growth activated-sludge plants. The investment costs of the plants appeared to be proportional with flow rate and not related to the type of plant. Total treatment costs varied between 0.10 and 0.19 USD/m^3. Deficient performance was found in non-mechanized and mechanized plants and did not seem associated with technology choice, but rather with the operation and maintenance regime. As fixed-film reactors appeared to be more capable of retaining active sludge in the aeration compartments, they seemed more appropriate to the low sewage strength than suspended-growth reactors in the situation under study. In accordance with (Euler et al., 2001) it is concluded, that prerequisites for good decentralised wastewater management are a clearly defined political will to solve environmental problems, effective legal requirements, technological knowledge and an enabling social and technical environment. The willingness of treatment plant owners to keep a plant operating was a crucial success factor. The Vietnamese practice of small sewage-treatment plants needs a thorough improvement. Several recommendations for design, construction, operation and policy enforcement are proposed, among which are rationalization of effluent standards, demonstration-scale research of sewage treatment, the issuing of design guidelines and professional standardized operation of plants.

CHAPTER 10 DRAINAGE AND SANITATION SYSTEM SELECTION FOR HO CHI MINH CITY

10.1 Introduction

The present chapter demonstrates the application of the SANCHIS screening aids and information data base elaborated in chapters 5 until 7 for drainage and sanitation system selection and assessment using the example of Ho Chi Minh City. On the one hand this chapter selects appropriate options in a systematic way, on the other it is a validation of the SANCHIS method.

In section 10.2 three different types of built-up areas are distinguished with relation to the conditions for an improved drainage and sanitation infrastructure. Subsequently, in section 10.3 the feasible drainage and sanitation system options for these three types of residential areas are selected making use of the screening aids described in chapter 6. Then in 10.4 the most suitable technologies for the different elements of the drainage and sanitation systems are discussed. In section 10.5 the performance matrix of two selected feasible options is constructed making use of the data of chapters 6 and 7. Finally, in section 10.6 the outcomes are summarized delivering the most appropriate systems for Ho Chi Minh City.

10.2 Classification of residential areas

Up to very recently the urban drainage and sanitation systems in Vietnam were characterized by the absence of off-site wastewater treatment. C*ombined sewer* options are most feasible under this condition and in fact to be found in the central zones of many cities. In order to reduce the risk of clogging of pipes and reduce the pollution emissions to surface water from these otherwise untreated options, household septic tanks for treatment of black water or black plus grey water are widely used (chapter 8).

Three types of residential areas are distinguished with respect to the improvement of drainage and sanitation infrastructure, namely (1) new residential areas, (2) existing upgrading areas, and (3) high-rise buildings. The different conditions in these residential areas justify different types of drainage and sanitation infrastructure. Since Vietnamese law does not permit untreated discharges of wastewater, selected options all must be provided with treatment up to secondary level[232]. The selection is carried out using the screening aids detailed in chapter 6. The next subsections describe the situation in the three different areas in terms of the questions posed in the screening aids. A summary of the conditions is given in table 10.1. In this description Ho Chi Minh City is taken as an example. The degree to which Ho Chi Minh City can be considered representative to other Vietnamese cities is discussed in section 10.6.

10.2.1 New residential areas

The *new residential area* considered in table 10.1 is built for the middle to high-income bracket with a mixture of individual houses, row houses and high-rise apartment buildings. These houses all have piped water supply in the house.

[232] Removal of BOD_5 to 30 mg/l and TSS to 50 mg/l (TCVN 6772-2000)(Annex A.1.2).

Table 10.1 Conditions in new residential and upgrading areas in Ho Chi Minh City with respect to the selection of drainage and sanitation infrastructure.

Questions posed in screening aids[233]	New residential area and high-rise buildings	Urban unplanned upgrading area
Is household water hand carried?	No, there is piped supply	No, there is piped, rarely hand-carried, supply
Is building density high?	Yes, it is moderate to high in the range of 200 – 400 inhabitants per hectare	Yes, over 400 inhabitants per hectare: high to very high
Is annual rainfall moderate or low?	No, it is high	
Is annual rainfall high with high intensities	Yes, annual rainfall is 1800 mm[234]. The design rainfall[235] at a return period of 2 years and duration of 30 minutes equals 94 mm/hr. This is considered a high annual rainfall with very high intensities. Due to a high building density the runoff factor is high (over 0.8)	
Has resource recovery priority?	No, recovery has no high priority at present, but should be set as policy objective in the near future[236]	No, recovery has no priority in these areas
Is direct agricultural reuse of WWTP effluent possible?	Yes, but possible only after treatment in very small and large plants	No, not possible, due to lack of space
Do households use low volume flush toilets?	Yes, both high and low volume flush toilets are used	Yes, pour-flush (low volume) toilets are predominant
Is water supply regularly interrupted?	No, water supply is rarely interrupted. In high-rise buildings there are no interruptions	Yes, water supply is often interrupted
Is the available slope for gravity flow small?	Yes, the building terrain is flat, so that gravity flow would need wide pipes and low velocity or much digging.	
Are small-bore sewers used?	No	Yes, small-bore sewers are used to reduce costs
Is reduction of pollution emissions, due to separated stormsewer overflows, required?	No, according to legislation no special measures have to be taken to reduce discharges of stormsewers to receiving water	

The building density is moderate to high (200 – 400 inh/ha) and streets are wide enough to build sewers and give access to vacuum tank trucks. The run-off factor is rather high, which

[233] This thesis, section 6.7, figures 6.7.1, 6.7.2, 6.7.3 and 6.7.4.
[234] Statistical Office Ho Chi Minh City (2007).
[235] The design rainfall intensity of Ho Chi Minh City has been calculated with the equation $I = b/(t^n + a)$ in which t is the time of concentration and a, b and n are constants (after (JICA/ Pacific Consultants International, 1999a), Figure C.11).
[236] Author's view based on need of saving and recovery of natural resources.

leads to relatively limited rainwater infiltration and, in combination with frequent high rainfall intensities, to a large runoff flow. Recovery of resources (water, energy, N and P) has no high priority in the policy of Vietnamese cities at present, but the author assumes recovery as a future requirement.
Agricultural reuse is considered as a feasible reuse option, especially useful in the driest months of the year. However, it relies on the availability of reserved agricultural areas in new urban zones or long-distance transport of treated effluent to zones in the periphery of the city. At present reservation of spaces for urban agriculture is not a part of the planning policies in Vietnamese cities.

10.2.2 Unplanned upgrading areas

Urban unplanned upgrading areas are scattered all over Ho Chi Minh City. They are characterized by an increasing rate of piped water supply, a high building density in the range of 300 – 1,000 inhabitants per hectare with very little green space and often very narrow streets which do not give space for vacuum trucks. The highest environmental priorities in these areas, besides water supply and solid waste management, are flooding control and reduction of pollution of local receiving waters.

10.2.3 High-rise buildings

By virtue of their highly localized generation of wastewater high-rise buildings used for residential or office purposes may offer special opportunities for resource saving, recovery and reuse. Feasible systems for such buildings are discussed in section 10.3.3.

10.3 Selection of feasible drainage and sanitation systems

10.3.1 Feasible drainage and sanitation systems for new residential areas

Making use of the description of the situation of table 10.1 and the decision trees (figures 6.7.1 and 6.7.2) options of system groups 6, 7, 10, 11 and 12, that is options with separated drainage of stormwater and sewage, appear being feasible to new residential areas in Ho Chi Minh City. The main factor that leads to this conclusion are the frequent high rainfall intensities which result in mighty flows of stormwater for which long transport distances have to be avoided. System group 6 consists of system options with regular flush toilets (pour-flush, cistern-flush, dual flush). The options of system group 7 have urine-diverting flush toilets with the storage of urine in tanks, regular collection and reuse in agriculture. System group 10 has urine-diverting (dry) dehydrating toilets. Urine and faecal matter are collected separated by cartage. As there are many uncertainties about the suitability of this system in dense urban areas with multi-storey houses, this group is eliminated from the selection. System groups 11 (vacuum toilets and sewerage), and 12 (local black water reuse) are high-tech source-oriented options probably exclusively suitable to selected communities and individual large buildings. Due to their high-tech nature these options are considered unfeasible for Vietnamese residential areas. Accordingly, the groups feasible in the situation under study are:

Flush toilets plus separate sewer systems with discharge of wastewater-treatment plant effluent to surface water or with reuse of effluent on agricultural land (system group 6);
Urine-diverting flush toilets plus separated sewer systems (system group 7).

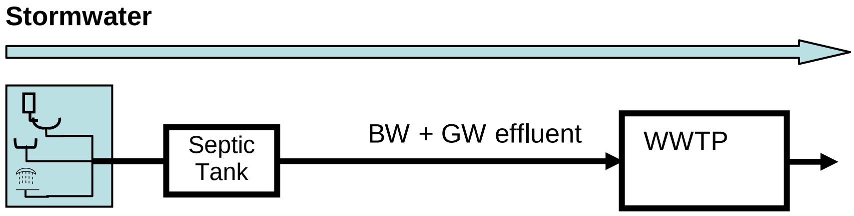
For finding feasible options *within* these system groups the aid of figure 6.7.4 is used. It is assumed here that stormwater treatment is not required, so that the improved separate system options 6B, 6D, 6F, 7B, 7D and 7F can be eliminated from the selection.
It is concluded that the separate sewer systems 6C, 6E (with flush toilets), 7C and 7E (with urine-diverting flush toilets) are feasible in *new residential areas* in Vietnam (figure 10.1 and 10.2). Where gravity transport does not satisfy, the pumped, but otherwise similar, options 6C(P), 6E(P), 7C(P) and 7E(P) can be necessary.

10.3.2 Feasible drainage and sanitation systems for unplanned upgrading areas

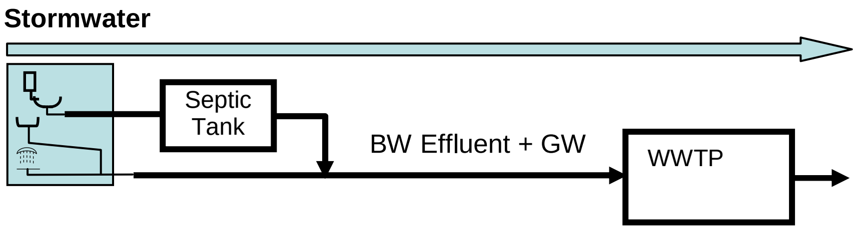
Similar to new residential areas the first screening for unplanned upgrading areas with figure 6.7.2 leads to separate sewerage systems. Since the priority in the area is on control of flooding and adequate sanitation and not on resource recovery, the screening favours options of group 6 (flush toilets with separated stormwater and sewage transport). Options of group 7 (urine-diverting flush toilets) are excluded, as their installation in existing high-density areas is deemed complicated. The screening of the options of system group 6 by means of the aid of figure 6.7.4 leads to the options 6C and 6E, where 6C is a separate sewer system with a septic tank for black and grey water and option 6E has a septic tank for black water only. If pumping of sewage is needed due to lack of natural slope and long distance of transport, the pumped options 6C(P) and 6E(P) could be feasible instead. In summary, the feasible drainage and sanitation options in new residential areas and existing upgrading areas are depicted in figures 10.1 and 10.2.

10.3.3 Feasible drainage and sanitation systems for high-rise buildings

In Vietnamese cities many high-rise buildings are erected for residential and public-commercial use. If no special resource- recovery measures are planned, these buildings can be equipped with the separate sewerage options of group 6, similarly to the residential areas surrounding these buildings (figure 10.1). If resource recovery receives priority, options of system groups 7 (segregation of urine from brown + grey water), 11 (vacuum toilets, segregation of black and grey water and localized energy recovery from black water) and 12 (segregation of urine, brown water and grey water) could be feasible (figures 10.2 and 10.3). The compact nature of the infrastructure in these buildings supports these options, since it reduces the costs and enables professional operation and maintenance of local small wastewater-treatment plants. In high-rise buildings there are no household septic tanks, but there could be primary plus secondary wastewater-treatment plants mounted below or near the building (e.g. chapter 9: Petrovietnam Building). Effluent could be reused for toilet flushing, biogas could be recovered for utilization, and urine could be collected separately for re-utilization in agriculture or recovery of phosphorus.

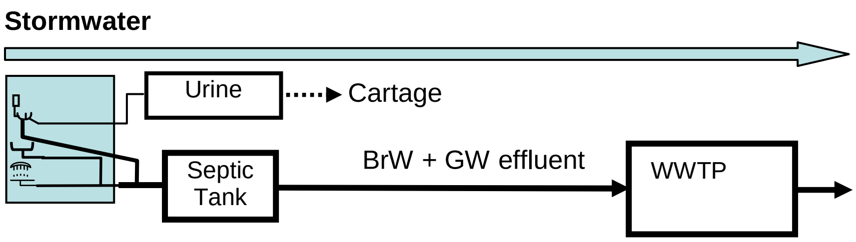


Option 6C: Settled separate sewer system

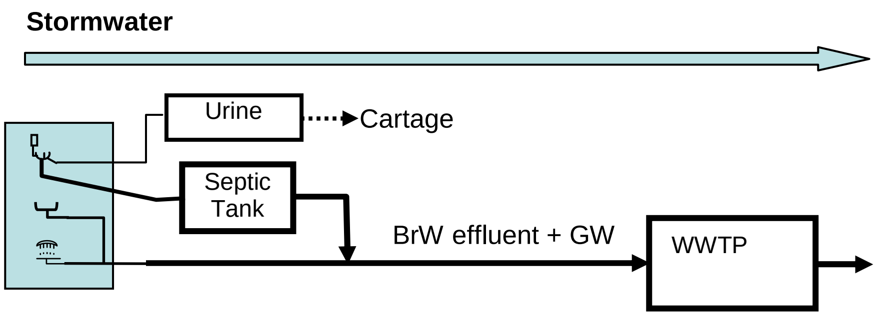


Option 6E: Settled separate system with grey water bypass

Figure 10.1 Feasible drainage and sanitation options for new and upgrading residential areas in Ho Chi Minh City.

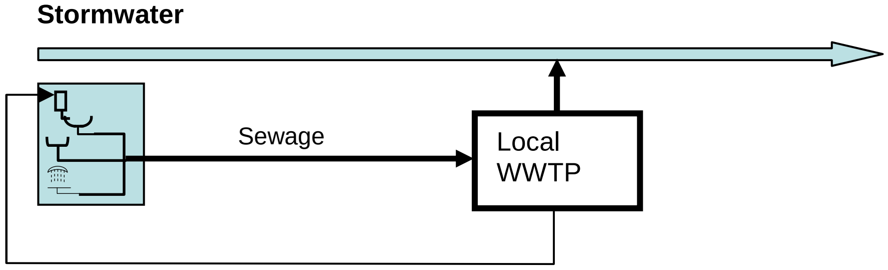


Option 7C: Settled separate system with urine-diverting flush toilets; brown and grey water treated in septic tank

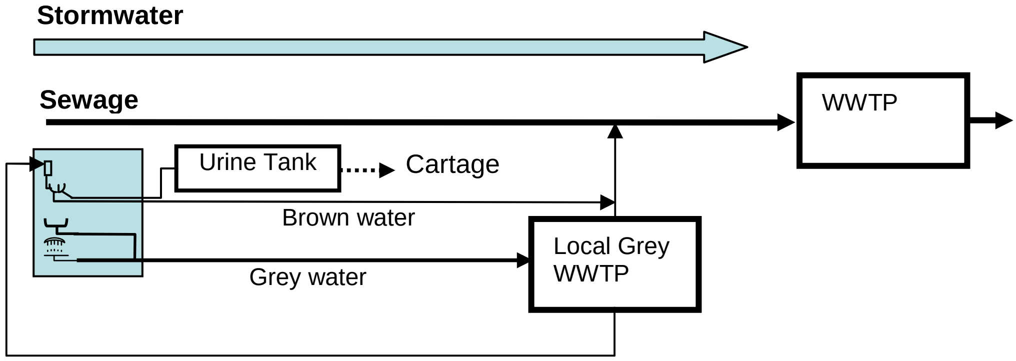


Option 7E: Settled separate system with urine-diverting flush toilets; brown water treated in septic tank

Figure 10.2 Feasible drainage and sanitation options with urine-diverting toilets for new residential areas in Ho Chi Minh City.



Option 6A: Plain separate sewer system with flush toilets; local treatment and reuse of WWTP effluent for toilet flushing (group 6)



Modified option 12A: Separate system with urine-diverting flush toilets; local treatment of grey water and reuse of grey-water treatment plant effluent for toilet flushing

Figure 10.3 Feasible drainage and sanitation options for high-rise buildings in Ho Chi Minh City.

10.3.4 Drainage and sanitation system options selected during SANCHIS workshops

The screening carried out during SANCHIS workshops in Ho Chi Minh City in 2007 has led to system groups 4 (option 4E) and 6 (option 6E), i.e. to settled combined and separate sewerage systems (chapter 11). This was in agreement with the proposals of the Urban Drainage and Sewerage Master Plan of Ho Chi Minh City (1999), in which both systems are planned (in different districts). Combined systems were prescribed in districts that already have these systems, and separate systems in new building areas.

Due to the fact that in the densely built neighborhoods under study the households have no place for private flush toilets and visitors have to be accommodated, the workshops recommended communal toilet blocks with flush toilets as improvement of the drainage and sanitation infrastructure. Due to the high rainfall intensities and a high frequency of combined sewer overflows, considerable discharge of pollution to surface water may be expected, unless extra storage capacity in the form of retention basins is provided (options 4D and 4F). In zones where separate sewerage is chosen long transport distances of the large flows of stormwater will have to be avoided in order to limit pipe costs. The stormwater has to be discharged to the closest surface water. Reduction of surface-water pollution from stormsewers requires regular cleaning of streets and gullies, in particular at the end of the dry season, and retention of sand, sludge and solid waste by means of built-in waste traps, rather than the application of the more complicated improved separated system (e.g. option 6D).

In summary, the workshops concluded that the most feasible drainage and sanitation systems in new residential zones of Vietnamese cities are the settled separate sewer systems with stormwater discharge to the nearest available surface water (options 6C and 6E). Where gravity flow is too slow, pumping of sewage will be required (options 6C(P) and 6E(P)).

10.4 Selection of feasible technologies for new residential areas

Within the systems selected above several technological possibilities are available for the processes in the drainage and sanitation chains. These are defined in this section in the subsections 10.4.1 until 10.4.5.

10.4.1 Toilet choice

The selected system options of group 6 (6C and 6E) could be equipped with pour-flush, standard cistern-flush or dual flush toilets. Here, dual-flush toilets are assumed as they fit best with the living standard of new planned residential neighborhoods in Vietnamese cities and use less water than regular flush toilets. The options 7C and 7E make use of urine-diverting flush toilets. Characteristics of these toilet types can be found in section 6.2.

10.4.2 On-site treatment technology choice

The selected system options 6C, 6E, 7C, 7E for new residential areas require some form of on-site suspended solids removal from respectively black and grey water (6C), black water (6E), concentrated brown and grey water (7C) and concentrated brown water (7E) prior to discharge into the sanitary sewers. Indicative values of the flow-rates, COD_{tot} loads and COD_{tot} concentrations of the influent received at the on-site pre-treatment processes for the selected system options are shown in table 10.2. These values are derived from tables 5.1 and 5.2. In urine-diverting flush toilets only 50% of the urine is separated from the brown water.

Table 10.2 Wastewater flows, loads and concentrations received at the on-site pre-treatment process in selected system options (6C – 7E) for new residential areas (indicative values).

System option	Wastewater to on-site pre-treatment	Flow-rate (l/cap.d)	COD_{tot} load (g/cap.d)	COD_{tot} concentration (g/l)
6C	Black and grey	119	109	0.91
6E	Black	29	57	1.95
7C	Concentrated brown and grey	97	103	1.1
7E	Concentrated brown	6.6	51	7.7

According to screening by means of the restrictive factors (table 6.3.5) the on-site pre-treatment technologies feasible in Vietnamese cities are the horizontal-flow septic tank (HFST) and the horizontal-flow septic tank with anaerobic filter (HFSTAF), the UASB septic tank without biogas utilization and the baffled anaerobic septic tank (BAST). The most relevant data for performance comparison of black-water septic tanks are shown in table 10.2. These data come from chapter 6 and 7.

Table 10.3 Performance data for household septic tanks treating domestic black water (source: section 6.3 and 7.4).

Parameter	Unit	HFST	HFSTAF	UASB-ST	BAST
Low sensitivity to irregular maintenance	Scale 1 – 5 (5 = best)	5	4	4	5
COD_{tot} removal	%	40	60	75	75
CH_4-emissions[237]	g CH_4-COD/ cap.d	16	24	30	30
Indicative construction costs[238]	USD/household	200	400	250	250
Proven performance in:		Field	Field	Research	Research

The horizontal-flow septic tank is widely used in Vietnam, while the UASB septic tank and the baffled anaerobic septic tank were tested in experiments, but not applied on a mass production basis. Where one pre-treatment unit serves a cluster of households the UASB-septic tank with biogas utilization and the Imhoff tank may be applied as well. In the comparison of options 6E and 7E in section 10.5 the horizontal-flow septic tank (HFST) is proposed as the most appropriate on-site treatment technology for black water (6E) and brown water (7E) by virtue of its low sensitivity to irregular maintenance and proven performance. It has been assumed that the COD removal efficiency for both black and brown water is 40%[239].

10.4.3 Transport technology choice

The selected drainage and sanitation systems 6C, 6E, 7C and 7E all have septic tanks for solids removal prior to transport. Although for transport also a regular-bore sanitary sewer system could be chosen, it is proposed here to make use of the less expensive small-bore system for transport of pre-settled brown and black water and grey water. Where feasible the principle of condominial sewerage could be applied to the lay out of the settled sewerage system to reach a significant costs reduction (subsection 6.4.4).

10.4.4 Off-site wastewater-treatment technology choice

The abovementioned screening for new residential areas in Ho Chi Minh City resulted in separate sewer systems with four different types of wastewater to be treated with off-site treatment plants (figures 10.1 and 10.2). The COD concentrations of the influent to the off-site treatment for the system options 6C, 6E, 7C and 7E are respectively 0.55, 0.72, 0.64 and 0.86 g COD/l. This means that in all options the influent has the strength of domestic sewage, though the suspended solids concentrations could be lower than those found in raw sewage by virtue of the pre-treatment step. Entrance of rain and groundwater into sanitary sewer lines should be prevented.

Screening of feasible primary plus secondary wastewater-treatment technologies is carried out by means of the decision tree shown in figure 6.5.5.1. The conditions in Ho Chi Minh City and their consequences to the choice of wastewater-treatment technologies are summarized in table 10.4. In the table the distinction is made between medium-scale plants with a flow rate

[237] See table 6.3.3: anaerobic pre-treatment systems loaded with black water.
[238] See table 7.4: direct construction costs.
[239] There is no experience with the treatment of concentrated brown water from urine-diverting flush toilets (COD_{tot} concentration is in the order of 8 g/l) in septic tanks.

between 1,000 and 10,000 m^3/d and small-scale plants (< 1,000 m^3/d). The borderline between small and medium/large scale plants is rather arbitrary. An important consideration behind this large versus small classification is the supposed better operation and maintenance of larger-scale plants, which results in different technology choices for the two classes.

On the basis of the assumed and generalized conditions in Ho Chi Minh City it is concluded that for *medium- scale installations* (> 1,000 – 10,000 m^3/d) treating the abovementioned types of wastewater high-rate anaerobic (UASB-reactor) and mechanized aerobic technologies are feasible. The latter can be used for main treatment or post-treatment of UASB-effluent. Non-mechanized methods, such as ponds and wetlands, are deemed unfeasible, due to lack of land. It should be noted that at present UASB reactors are not used for sewage in Ho Chi Minh City, due to the prevailing low influent COD, which is attributed to dilution of sewage with rainwater and groundwater in the combined sewer lines. If such dilution in the separated sewer system can be avoided, UASB reactors could be an attractive treatment option.

For *small installations* (< 1,000 m^3/d) on the one hand mechanized technologies are excluded, based on the fear of failing maintenance[240], but on the other hand it can be assumed that ponds, and constructed wetlands can be applied where their use is anticipated in the land planning of new residential zones. The feasible option for existing high-density areas is Imhoff tanks followed by anaerobic upflow filters. Where household septic tanks are widely used and effective, the collected sewage may contain few solids and the Imhoff tank can be omitted. The BOD treatment efficiency of the combination of septic tank and anaerobic upflow filter is in the range of 70-85 % (subsection 6.5.3.7). To the author's knowledge no data are available on the efficiency differences between anaerobic upflow filtration applied to the effluents of septic tanks treating black plus grey water and the same technology applied to the mixture of grey water and effluent of septic tanks treating black water only. The effluent quality of the mentioned sanitation system of septic tank or Imhoff tank and anaerobic upflow filter may not (always) comply with the Vietnamese standard (TCVN 5945-2005 (B)) for $COD/BOD_5/TSS$ = 80/50/100 mg/l. Further research could elucidate the strengths and weaknesses of anaerobic upflow filters in this application.

[240] The survey of small-scale secondary wastewater-treatment plants in Vietnam reported in chapter 9 showed that operation and maintenance often failed and that therefore non-mechanized technologies are preferable.

Table 10.4 Conditions in Ho Chi Minh City and consequences for the choice of off-site wastewater-treatment technologies.

Wastewater treatment Parameter	Conditions in HCMCity	Consequences
Ambient temperature	> 20°C.	All anaerobic and aerobic non-mechanized and mechanized treatment options
Feasibility of mechanical treatment (Guarantee of skilled maintenance, power and spare parts)	Mechanized treatment is feasible in medium-scale installations in cities; feasible in high-rise buildings	In medium-scale installations: mechanized and non-mechanized technologies
	Unfeasible for small installations in residential areas	Small-capacity: non-mechanized technologies
Guarantee of frequent basic maintenance	Available for medium-scale installations and high-rise buildings;	Large and medium-scale installations: no restrictions to choice of technologies
	Not available for installations < 1000 m^3/d in residential areas	Small installations (< 1000 m^3/d): Imhoff tanks, anaerobic upflow filters, stabilization ponds, constructed wetlands and soil infiltration
Availability of inexpensive land for WWTP	Land price is generally high. Very limited land is available at neighborhood level	Medium-scale installations: compact high-rate anaerobic and mechanized aerobic technologies
	Land may reserved for multifunctional use	Small installations (< 1000 m^3/d): Imhoff tanks, anaerobic upflow filter, subsurface-flow constructed wetlands, ponds
Availability of inexpensive filter medium	Unknown.	Subsurface flow constructed wetlands require inexpensive filter medium
Permeability of soil	Depends on location	Rapid soil infiltration requires a permeable soil
Water table	Depends on location	Rapid soil infiltration requires a low water table (> 5 m deep)
Conclusion wastewater treatment	Medium-scale plants (1,000 - 10,000 m^3/d) and plants belonging to hige-rise buildings: (1) High-rate anaerobic pre-treatment (UASB) and mechanized aerobic post-treatment technologies; (2) mechanized aerobic treatment Community-level systems (< 1,000 m^3/d): Imhoff tanks + anaerobic upflow filters, subsurface-flow constructed wetlands and ponds	

10.4.5 Handling of effluent and urine

In Ho Chi Minh City effluent of wastewater-treatment plants is discharged to surface water. Other obvious options would be reuse in agriculture or for watering of green spaces. In both options specific quality requirements could make further post-treatment necessary. In the selected options 6C, 6E, 7C and 7F the effluent is not reused. The options 7C and 7E with urine-diverting toilets yield urine as a reusable product (fig 10.2). The treatment options for urine have been described in chapter 6.

10.4.6 Feasible drainage and sanitation systems in Ho Chi Minh City

The sections above demonstrate the selection of feasible drainage and sanitation options for Ho Chi Minh City. A distinction is made between new residential areas, existing upgrading areas and high-rise buildings. The results are summarized in the table 10.5.

Table 10.5 Results of the screening of drainage and sanitation and wastewater treatment systems for Ho Chi Minh City.

Application	Feasible drainage and sanitation systems	Feasible wastewater-treatment technologies
New residential areas	System Group 6: flush toilets and settled separate sewerage	< 1,000 m^3/d: anaerobic upflow filtration; subsurface-flow constructed wetlands; ponds 1,000 – 10,000 m^3/d: High-rate anaerobic pre-treatment (UASB) + mechanized aerobic post-treatment technologies; mechanized aerobic treatment
	System group 7: urine-diverting flush toilets and settled separate sewerage	As system group 6 plus utilization of urine
Existing unpanned upgrading areas	System group 6: (pour-) flush toilets and settled separate sewerage	< 1,000 m^3/d: anaerobic upflow filtration 1,000 – 10,000 m^3/d: see new residential areas
High-rise buildings	System group 6: flush toilets and separate sewerage; System group 7: urine-diverting flush toilets and separate sewerage	Local mechanized secondary aerobic biological treatment + tertiary treatment for effluent reuse
	System group 11: vacuum toilets and separate handling of 3 waste streams; System group 12: urine-diverting toilets and separate handling of 4 waste streams	Possibilities of local generation of energy from wastewater and reuse of effluent

For *new residential areas* the feasible options belong to system groups 6 and 7. System group 7 includes options with urine-diverting flush toilets. With regard to wastewater treatment a distinction is made between small-scale and larger scale treatment (10.4.4). As under the conditions of new residential areas external supplies and frequent maintenance can be warranted, the use of mechanized aerobic biological treatment technologies, such as suspended-growth activated sludge and submerged aerated fixed-film reactors, could be considered. The selection of the most acceptable option out of feasible options of system groups 6 and 7 is demonstrated in the next section 10.5.

Where local wastewater treatment is required in *existing high-density upgrading areas* only options of system group 6 are feasible. These options belong to the separated settled sewer systems (options 6C and 6E and their pumped versions 6C(P) and 6E(P)). The wastewater treatment takes place in two steps: on-site by means of a septic tank and off-site by means of anaerobic upflow filtration. The SANCHIS screening aid selects the latter system, because of its low required skills for maintenance, its low dependence on external resources (energy, spare parts, professional surveillance), and low space requirements. For *high-rise buildings* in addition to the options of system group 6 and 7 also options of group 11 and 12 are deemed feasible.

10.5 The performance comparison of feasible options

10.5.1 The results of screening

While section 10.4.5 shows the outcomes of the application of the screening aids to three different situations in Ho Chi Minh City, this section demonstrates how the SANCHIS method can be applied for *comparison* of options for a concrete situation. The options selected for comparison are the options 6E and 7E, which are both feasible in new planned residential areas of Ho Chi Minh City (figure 10.1 and 10.2). Option 6E is a separated sewer system using regular flush toilets and horizontal-flow septic tanks for on-site pre-treatment, and option 7E is a similar settled separated sewer system that uses urine-diverting flush toilets. The collected urine is stored locally and transported to agricultural areas for reuse. The selected wastewater-treatment technology is the UASB reactor with post-treatment in a submerged aerobic filter. The latter was chosen for post-treatment by virtue of its expected high operational reliability in Vietnam (chapter 9).The effluent is discharged to surface water.

10.5.2 Comparison of options 6E and 7E

In the comparison of options it is of first importance to find out in what respects the systems are different, since the data collection can subsequently focus on these differences. In many respects option 6E can be considered as a reference option, since it applies conventional technologies. Option 7E includes urine-diverting flush toilets, urine storage, cartage and reuse, so that less N and P is received at the wastewater-treatment plant and in the discharged effluent. Details of the options are given in table 10.6.

Table 10.7 is the performance matrix for the two options. Criteria 1 (compatibility with local physical and infrastructure conditions) and 2 (compatibility with policy framework) have been omitted since they are screening criteria that the two options satisfy anyhow. For each of the technology-specific criteria stipulated in chapter 4 it has been indicated whether the performance differences are negligible or significant/ calculable. A distinction is further made between qualitative and quantitative performance scores. For option 6E the qualitative performance scores are indicated with ‘0’, meaning reference value. For option 7E the qualitative performance scores are rated in comparison with option 6E by either ‘-‘ or ‘+’ , meaning that the criterion is fulfilled to a lower or higher degree in comparison to the reference option 6E.

Table 10.6 Characteristics of the compared options 6E and 7E.

Elements	Option 6E	Option 7E
Toilet type	Dual flush toilet; Flush water volume: 28 l/cap.d	Urine-diverting flush toilet; Flush water volume: 6 l/cap.d
Urine separated at source	0 %	50 %
Urine volume to sewers	1.25 l/cap.d	0.6 l/cap.d
Grey water	90 l/cap.d	90 l/cap.d
On-site pre-treatment	Black water HFST COD removal: 40% N removal: 3% P removal: 7%	Brown water HFST COD removal: 40 % N removal: 3 % P removal: 7 %
Sewer system	Separated collection of stormwater and sewage; Small-bore sewers where possible	
Off-site treatment	UASB + submerged aerated fixed film reactors; Overall COD removal: 80 – 85 %; Overall N removal: 35 – 45 %	
Effluent disposal/reuse	Discharge to surface water after treatment	
Stormwater disposal/reuse	Discharged to surface water without treatment	

With regard *to technical criteria* (3-7) option 7E differs from option 6E with respect to the *sensitivity to irregular maintenance* (5) and *independence of external supplies and services* (6). Collection and transport of urine in option 7E require a regular and reliable service. This service could be integrated into the collection of domestic solid wastes. The urine-collection pipes and tanks have to be regularly inspected and cleaned to avoid clogging with precipitates. Accordingly the technical performance score for option 7E is lower than for option 6E.

In the domain of *health criteria* (8-11) the urine handling and reuse in option 7E could lead to *exposure of waste workers* (*criterion 9*) and *workers during reuse in agriculture* (*criterion 10*). Such exposure does not occur in option 6E. The impacts of this exposure, however, are rated low. Nevertheless the health performance score for option 7E is rated slightly lower than for option 6E.

With respect to the *environmental criteria* (12-19) the urine diversion leads to differences with respect to COD, N and P load of the wastewater-treatment plant and consequently to the *effluent quality and emissions*. The emissions and possibilities of recovery are estimated on the basis of a material flow analysis. An overview of the COD, N and P mass balances for the two options is presented in figures 10.5 and 10.6. The calculations are based on the modelled fate of COD, N and P in the septic tank, UASB reactor and submerged aerated filter for the two options 6E and 7E. The values of COD, N and P loads in black and grey water are those mentioned in table 5.2. It has been assumed that there is no removal of COD, N and P in the sewer lines[241]. Here, COD should be read as COD_{tot}.

[241] The influent COD, N and P loads (black + grey water) used in the calculation of the material flows are 109, 13.5 and 2.0 g/cap.d respectively (table 5.2).

Table 10.7 Comparison of performance of drainage and sanitation options 6E and 7E.

Nr	Criterion	Unit	Performance Option 6E	Option 7E
3	Low level of skills needed in construction	-	Negligible differences	
4	Low level of skills needed in operation	-	Negligible differences	
5	Low sensitivity to irregular maintenance	-	0	-[242]
6	Independence of external supplies (e.g. power, chemicals) and services	-	0	-
7	Ease of adaptation to fluctuations and new requirements	-	Negligible differences	
8	Prevention of exposure of users	-	Negligible differences	
9	Prevention of exposure of workers	-	0	-
10	Prevention of exposure during reuse	-	0	-
11	Prevention of exposure downstream population	-	Negligible differences	
12	Low COD emissions to water	g COD/cap.d	15.1	14.5
		Removal %	86 %	87 %
13	Low N and P emissions to water	g N/cap.d	N = 8.1	N = 4.8
		N Removal %	40%	64%
		g P/cap.d	P = 1.6	P = 1.2
		P removal %	20%	40%
14	Low methane emissions to atmosphere	g CH_4-COD/ cap.d	23.7	20.5
15	Low malodours and insects nuisance	-	Negligible differences	
16	Low emissions soil and groundwater	-	Negligible differences	
17	Consumed Water	l/cap.d	118	96
	Recoverable water		Negligible differences	
18	Consumed energy	MJpe/cap.yr	151-216	109-156
	Recoverable energy		145	144
19	Recoverable nitrogen	g N/cap.d	2.7	7.1
		N recoverable	20%	53%
	Recoverable phosphorus	g P/cap.d	0.5	0.8
		P recoverable	25 %	40 %
20	Low requirements to institutional support/cooperation through the chain	-	0	-
21	Low requirements with respect to end-user awareness	-	0	-
22	High convenience and cultural acceptability	-	0	-
23	Consideration to issues of women, children, elderly and disabled	-	Negligible differences	
24/25	Low costs/ high benefits (TACH)	USD/hh.yr	872[243]	856[244]

[242] 0: reference performance (system option 6E); + / - performance is better/worse than reference (option 6E).
[243] See table 7.21: the compared options are 6A and 7A in Germany, costs of stormwater drainage excluded (after (Oldenburg, 2007) Comparable costs of options 6E and 7E are expected.

COD emissions (*criterion 12*) with the effluent are not much different for the two options (option 6E: 15.1 g COD/cap.d; option 7E: 14.5 g COD/cap.d). The overall COD removal percentages, calculated as $COD_{effluent}$ / $COD_{generated}$, are 86% and 87% for the options 6E and 7E respectively. The diversion of urine in option 7E leads to reduced *N and P emissions* (losses) with effluent. In options 6E and 7E the N emissions to receiving water are 8.1 and 4.8 g N/cap.d and the P emissions 1.6 and 1.2 g P/cap/d respectively. In both options N and P removal are the consequence of particle removal and uptake into biological sludge in the several stages of the treatment process. In the submerged aerated filters in addition nitrification and de-nitrification lead to a partial removal of nitrogen as N_2 gas. Based on overall N removal efficiencies of UASB + SAF plants a de-nitrification of 25% of the influent N to the SAF step has been assumed (Chernicharo, 2006); (Canziani et al., 1999). This yields N_2 emissions to the atmosphere of 3.0 g N/cap.d for option 6E and 1.8 g N/cap.d in option 7E.

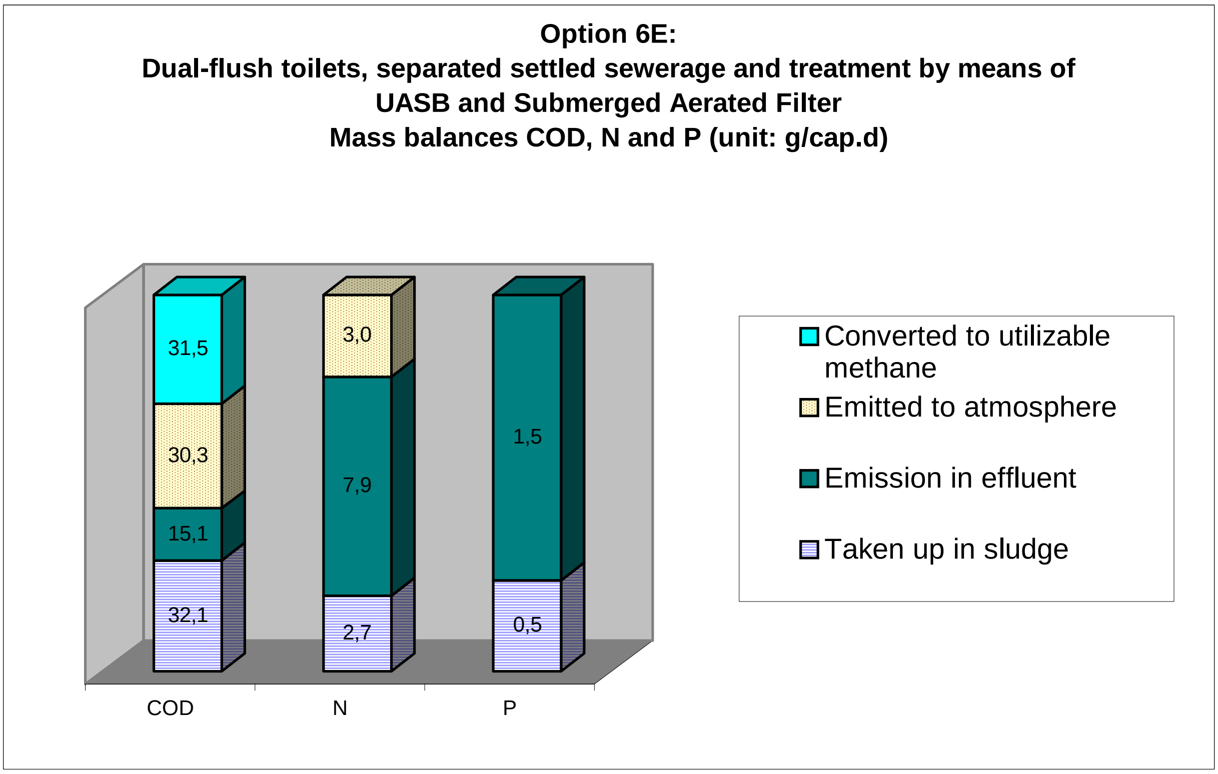


Figure 10.4 Mass balances of option 6E (regular dual-flush toilets).

[244] Benefits of water saving, energy saving, and nutrients recovery in options of group 7 are included in the TACH value.

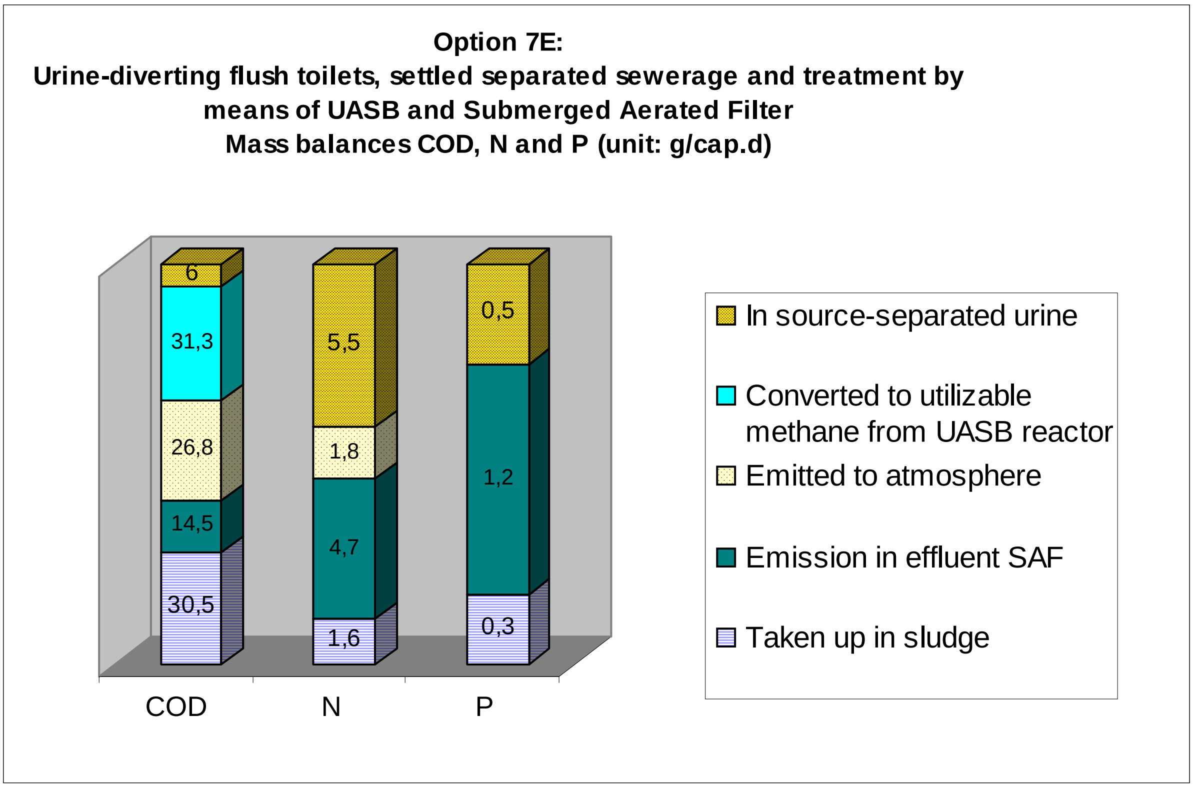


Figure 10.5 Mass balances of option 7E (urine-diverting flush toilets).

Methane emissions result from methane generated in the septic tank and methane dissolved in the effluent from the UASB reactor. The CH_4 emissions are 23.7 and 20.5 g CH_4-COD/cap.d for respectively option 6E and option 7E. It can be noted that this amounts to 22 and 20% of the influent COD. Option 7E is expected to have a slightly lower methane emission than option 6E due to the fact that in option 7E urine COD is not treated in septic tank and UASB-reactor. The total COD converted to atmospheric emissions amount to 30.3 and 26.8 g COD/cap.d for option 6E and 7E respectively (figures 10.4 and 10.5). In addition to the COD converted to methane these figures include the COD converted to CO_2 in the aerobic post-treatment step.

No difference between the two options is expected with respect to malodours and insect nuisance and emissions to soil and groundwater (criteria 15 and 16).
The use of urine-diverting toilets leads to an assumed *saving of water* of 22 liters/cap.d (*criterion 17*) in comparison to the dual-flush toilet. The latter type of toilet has an assumed water use of 28 and the first of 6 liters/cap.d. Incorrect use of the urine-diverting toilets might lead to a reduction of saving.

The assessment of the *net energy consumption* (*criterion 18*) requires the valuation of energy consumption and recovery (table 10.7). Energy is mainly consumed for conversion of COD and nitrification of ammonia in the post-treatment step. Since no data are found about energy consumption of the UASB-Submerged aerated filter combination, data of the UASB-activated sludge system are used instead. This consumption amounts to 50 – 72 MJe/cap.yr (151-216 MJpe/cap.yr) (table 6.5.12). It may be assumed that the energy demand in option 7E is lower than in option 6E, since significantly less ammonia is present and consequently less oxygen is needed for nitrification. Under the prevailing conditions the oxygen demand is 85.7 g/cap.d in option 6E and 61.8 g/cap.d in option 7E or 28% lower in option 7E. It is assumed that the consumed energy in option 7E is proportionately lower: 36 – 52 MJe/cap.yr (109-156 MJpe/cap.yr).

Energy can be recovered through capturing of methane from the UASB-reactor. Option 6E is expected to show a slightly higher methane generation than option 7E where 50% of the COD contained in urine (= 6 g COD/cap.d) is not received at the off-site treatment plant. The energy yields of the two options hardly differ: 145 MJpe/cap.yr for option 6E and 144 MJpe/cap.yr for option 7E). If the generated biogas would be used for generation of electricity with a generator efficiency of 33%, the electric power output would be 48 MJe/cap.yr for option 6E. An electricity output of 48 MJe/cap.yr corresponds to about 1.5 W/cap. The calculation of the balance of electricity consumption and recovery shows that the methane generation would cover 67 – 96% of the energy demand of the treatment plant in option 6E. In option 7E the produced energy could equal of even higher than the demand. In the mass balances (figure 10.4 and 10.5) this lost methane is accounted for in the category 'COD emitted to atmosphere'.

The *recoverable nutrients(N and P)*(*criterion 19*) consists of the sum of nutrients taken up in the sludges of the septic tank, the sludge generated in the UASB reactor and Submerged Aerated Fixed Film Reactor and – in the case of option 7E - of N and P contained in source-separated urine. The recoverable N and P amount to 2.7 g N/cap.d and 0.5 g P/cap.d in option 6E, and 7.1 g N/cap.d and 0.8 g P/cap.d in option 7E. Evidently, the source separation of urine leads to a higher fraction of recoverable nutrients. It has been assumed that waste sludges from the treatment processes are reused in agriculture without loss of nutrients. If this is not the case, the recoverable N and P are 0 in the case of option 6E and 5.5 g N and 0.5 g P/cap.d for option 7E (figures 10.5 and 10.6).

If in contrast to the assumptions made in the comparison of table 10.7 in both options the effluent of the wastewater-treatment plants would be used for crop irrigation instead of being discharged to surface water, additional recovery of N and P could be realized: the N recovery would increase from 20 to 78% for option 6E and from 52 to 87% for option 7E; the P recovery jumps from 24% to 100% in option 6E and from 42 to 100% in option 7E assuming that the collected excess sludge can be used as soil conditioner. The nutrient recovery for the sub-options are given in table 10.8.

Table 10.8 N and P recovery without and with effluent reuse for crop irrigation

	Option 6E				Option 7E			
	Without		With		Without		With	
	g/cap.d	%	g/cap.d	%	g/cap.d	%	g/cap d	%
N recovery	2.7	20	10.6	78	7.1	52	12.0	87
P recovery	0.49	24	2.0	100	0.85	42	2.0	100

The criteria in the domain of *social manageability* (*criteria 20-23*) are more difficult to attain in option 7E than in 6E. Option 7E puts higher requirements to *chain management* (20) as collected urine has to be reused; it demands a higher *end-user awareness* (21) as urine-diverting toilets and urinals have to be used correctly. In connection to this the *convenience and cultural acceptability* (22) of the urine-diverting system may need special attention. No significant differences are expected between the two options with respect to *issues of women, children, elderly and disabled* (23), though it has been noted that children could find it difficult to use the urine-diverting toilets in a correct way. This aspect has been covered by *criterion 21 (end-user awareness)*. The attainment of the *economic criteria* (24 and 25) will be slightly different for the two options. The values of *life cycle costs* (24) *minus benefits* (25) of the two systems are similar under the applied assumptions. On the side of the *benefits* (25) of the urine-diverting system avoided costs of flushing water, energy consumption in the treatment works, and chemical N and P fertilizer in agriculture can be mentioned, leading to slightly lower costs of option 7E. It should be noted that the costs of urine cartage in option 7E increase with transport distance. The underlying financial estimations are presented in chapter 7.

10.5.3 Conclusions of the comparison

The notable advantages of the system with urine-diverting flush toilets (option 7E) are a lower consumption of flush water in the toilets (22 l/cap.d), a lower energy consumption in the aerobic post-treatment step by virtue of a lower ammonia load, a lower N and P concentration in the effluent discharged to surface water, and an increased recovery of nitrogen and phosphorus through segregated collection and reuse of urine. The higher the segregated fraction of urine the more pronounced the advantages of the system. As was cited in chapter 6 (subsection 6.5.8) a maximum segregation of 75% is considered attainable under European conditions. It seems reasonable to assume that such a high rate of segregation can not be attained in Vietnam. Accordingly, in the example presented in the performance matrix a 50% urine segregation has been assumed. Contrary to the expectation the source-separating system 7E does not necessarily come with higher costs.

The question is of course whether the mentioned environmental advantages justify the extra efforts in the domain of management associated with the use of urine-diverting toilets and separated urine handling. Probably the required changes of management and domestic practices could be attained if sufficient political priority and users' acceptance can be created. If the effluent of the wastewater-treatment plant would not be discharged to surface water, but directly used for crop irrigation, the abovementioned advantages of segregated urine collection and reuse in option 7E are reduced to lower flush-water consumption and lower energy consumption. If effluent is reused directly, the recovery of phosphorus would be 100% in both options and of nitrogen 78% in option 6E (no segregated urine collection) and 87% in option 7E (with segregated urine collection) (table 10.8). The latter difference can be attributed to a lower loss of nitrogen to the atmosphere through de-nitrification in the submerged aerobic filter in option 7E. Consequently, direct reuse of effluent in irrigation using options of group 6 would be preferable to the use of options of group 7 wherever agricultural reuse is feasible and without unacceptable risks. In Vietnam direct reuse of treated effluent would be useful during the dry season only. Effluent generated in the rainy season would require storage, as there is no demand for extra irrigation water in this season. This requirement of storage in addition to long distance transport of effluent to fields may reduce the advantages of direct agricultural reuse.

The options comparison could raise questions about the use of household septic tanks as a pre-treatment step. These septic tanks have obvious advantages in prevention of clogging of the sewers and enabling the use of small-bore sewers, and thus in potential reduction of the costs of sewerage. However, they also lead to reduction of the COD-load to the UASB reactor and consequently to a lower production of utilizable biogas. Supply of COD from joint black and grey water would lead to a higher captured methane load so that the treatment plant could be self sufficient with respect to electrical energy. Accordingly, where biogas recovery from sewage is aimed at, the need of household septic tanks should be carefully considered.

10.6 Conclusions about drainage and sanitation system choice in Ho Chi Minh City

In the present chapter the SANCHIS tool is applied to select feasible drainage and sanitation systems for new residential neighborhoods, existing unplanned upgrading areas and high-rise buildings in Ho Chi Minh City. This selection is carried out through screening and comparison of feasible options on the basis of a system options list presented in chapter 5, taking into account the conditions of the intervention areas described in chapter 8 and 9 and summarized in table 10.1. Innovative drainage and sanitation options, that often are in a developmental stage still, have been included in the selection process in order to create awareness of future possibilities. For Ho Chi Minh City the following technical solutions were found.

New residential areas
2 feasible options were selected:

- High or low volume flush toilets with settled separated sewerage (system group 6, options 6C and 6E).
- Urine-diverting flush toilets with settled separated sewerage (system group 7, options 7C and 7E)

The collected sewage from both systems is treated by means of a wastewater-treatment plant consisting of UASB reactor and submerged aerated fixed-film reactor. Other post-treatment technologies could be feasible as well. The effluent is discharged to surface water or reused in agriculture. Urine is used in agriculture. Comparison of the options 6E and 7E specified the strength and weaknesses with regard to the technology-specific criteria of the SANCHIS method in table 10.7.

Unplanned upgrading areas
For unplanned upgrading areas the use of urine-diverting toilets was excluded. As the building density is high, household on-site solutions are not feasible. The selected options are:

- High or low volume flush toilets with settled separated sewerage (system group 6, options 6C and 6E).
- Ditto with pumping of sewage (system group 6, options 6C(P) and 6E(P)).

High rise buildings
High-rise buildings offer opportunities for reuse of effluent (e.g. for toilet flushing) and generation of energy from local wastewater-treatment plants.

If resource saving and recovery is not considered, a feasible option would be:

- High or low volume flush toilets with plain separated sewerage (system group 6, option 6A).

Where resource saving and recovery is required, there are several possibilities:

- Urine-diverting flush toilets with separated collection of urine, brown water/grey water (system group 7, option 7A);
- Urine-diverting flush toilets with separated collection of urine, brown water and grey water (system group 12 without application of on-site septic tank).

Stormwater in all feasible options is evacuated separated from other wastewater streams. Separately collected urine is used fro agricultural purposes.

In section 10.5 the performance with respect to technology-specific criteria is described of the two options (6E and 7E) which were selected for *new residential areas* (table 10.7). Comparison of the performances elucidates the strengths and weaknesses of the options.
Eventually, the question remains whether the extra efforts associated with segregated collection an utilization of urine (option 7E) counterbalance the benefits of this system. This would probably be so only if a high priority is given to nutrient recovery and direct effluent reuse is unfeasible.
A final assessment in preparation of the decision about system choice would require two additional steps: the assessment with regard to site-specific criteria (e.g. user acceptance) and the trading off of strength and weaknesses of the two options. Following the SANCHIS approach this assessment and trading off requires the participatory setting of a stakeholders workshop. The procedure is described in chapter 11.

The selection of options has been demonstrated using the conditions of Ho Chi Minh City as an example. Arguably, the selected options would be feasible as well in other Vietnamese densely populated cities, like Can Tho and Bien Hoa. Although this may be so, the basic principle of technology selection as advocated in this thesis requires seeking solutions based on careful analysis of existing situations and conditions, benefiting from the input of all relevant stakeholders, and therefore not copying solutions that work well in other places, even if these places seem very similar (chapter 2, principles 2, 3 and 5).

CHAPTER 11 PARTICIPATORY DECISION MAKING ABOUT SUSTAINABLE DRAINAGE AND SANITATION SOLUTIONS

11.1 Introduction

Overcoming the serious deficiencies of the drainage and sanitation infrastructure in Ho Chi Minh City, as described in chapter 8 and 9, requires enormous investments and is especially complicated in residential areas built under a poorly regulated planning regime. Similar challenges are encountered in other Vietnamese cities and towns. It has been argued in this thesis that a multi-stakeholder approach to planning, implementation and operation of infrastructure would be crucial to accelerate the realization of sustainable drainage and sanitation provision, in particular in low-income zones (chapter 2). The meant multi-stakeholder approach requires a method of participatory planning and decision-making that could assist actors in urban upgrading in selecting the most feasible drainage and sanitation solutions for various situations. Such a method, based on multi-criteria decision analysis of a wide range of options, has been developed in chapters 3 until 7. It is called SANCHIS, which stands for Sanitation Choice Involving Stakeholders. An important element in the SANCHIS process are workshops during which stakeholders select appropriate drainage and sanitation systems.

This chapter reports about the application and further development of the SANCHIS method during two workshops in Ho Chi Minh City in 2007. The main research questions during these workshops were:

- *What are the outcomes of SANCHIS method applied to drainage and sanitation problems in Ho Chi Minh City?*
- *How could SANCHIS be improved based on the experiences of the workshops?*
- *What are the perspectives and limitations of SANCHIS?*

These three research questions are addressed in the sections 11.2 - 4, 11.5 and 11.6 respectively. At the end of this chapter the hand-outs can be found used during the workshops to support the decision-making process (Annexes 11.1 - 4).

11.2 The basic lay-out of SANCHIS workshops

The principles of the SANCHIS method for participatory learning and decision making are described in chapter 3. In brief, the process of participatory drainage and sanitation planning consists of the following steps: selection and convening the relevant stakeholders (participants), problem analysis, design of feasible solutions to the identified problems, selecting the best solution and taking a decision. The design of feasible solutions encompasses three sub-steps: (1) determination of objectives/criteria, (2) selection of feasible options and (3) finding out these options' performance with respect to the chosen objectives.
The basic idea of the SANCHIS workshops is to lead the participants to a result through the planning stages by means of group assignments (table 11.1). Each stage is introduced in a plenary session followed by group assignments and plenary reporting of the group results.

Table 11.1 Stages of a SANCHIS workshop and working modes

	Stages of the SANCHIS workshop	Working mode
1	Problem analysis	Group assignment
2	Formulation of objectives/criteria for options	Introduction facilitator and Group assignment
3	Listing feasible options for drainage and sanitation improvement	Introduction facilitator and Group assignment
4	Listing performances of the options	Group assignment
5	Selection of the best option by trading off of performances	Group assignment and plenary calculation by facilitator of appropriateness indices

11.3 First SANCHIS workshop in Ho Chi Minh City

11.3.1 Organization and objectives

The first SANCHIS workshop was held at Van Lang University in Ho Chi Minh City during two half-day sessions in April and May 2007. It was organized by the author of this thesis to obtain experiences that could lead to further development of the SANCHIS method. The participants were technicians and lecturers in Environmental Technology and Management associated with CENTEMA and Van Lang University. Their interest was mostly to learn about the method and about feasible drainage and sanitation options for Ho Chi Minh City. The participants were placed in three subgroups of 6 persons, which each defined its own case area. They were given handouts about the group assignments, criteria, options and a decision aid (annexes 11.2-4). In the introduction of system options the emphasis was on the building blocks: toilets, on-site storage and treatment systems, transport systems, wastewater treatment and reuse and disposal. A few examples were shown of how these building blocks could be put together to a sanitation and drainage system, and it was expected that the participants would be experienced enough to create their own suitable systems on this basis. The workshop was completed with an individual written evaluation in which participants could give their views about the strengths and weaknesses of the method.

11.3.2 Results

The workshop groups produced a list of 8 criteria for good sanitation and drainage and 5 options for the case areas. They developed their performance matrices supported by a performance help-sheet, which briefly lists the strengths and weaknesses of the building blocks of the system options (A.11.3). The scores in the subgroups' performance matrices were inserted in an Excel spreadsheet for plenary computation and comparison. Subsequently, the groups ranked and weighted the relative importance of the criteria according to the method of swing-weighting shown in chapter 3. Table 11.2 shows the average weights and the variation of the attributed weights between the groups. Apparently, the groups judged the importance of the chosen criteria very differently. The groups attributed the highest weight to technical functionality of the selected options (0.35) and the lowest to low costs (0.14). Finally, the appropriateness score U_i for the options was calculated[245]. This score expresses

[245] $U_i = \sum_{k=1}^{K} w_k * u_{ik}$, in which U_i is the overall appropriateness of option i, w_k is the weight attributed to the criterion k and u_{ik} is the performance score for option i and criterion k (see chapter 3).

the suitability of the options in the situation under study. The result is shown in table 11.3. The participants found settled separate sewers with pump support (option 6E(P), chapter 5) with an average score of 72 % the most appropriate option for the unplanned flood-prone zones of the city.

Table 11.2 Result of the first workshop: selected criteria, their attributed normalized average weights and weight variation among subgroups.

Criteria for sanitation and drainage systems	Average weight	Weight variation among sub-groups
Technical		
▪ Compatibility with local conditions	0.18	0.15 – 0.22
▪ Reliability	0.17	0.10 – 0.22
Environmental		
▪ Emissions to water according to legal requirements	0.14	0.08 – 0.22
▪ Low other emissions (atmosphere, soil)	0.10	0.06 – 0.14
▪ Resource recovery	0.07	0.03 – 0.12
Social		
1. Availability adequate institutional support	0.10	0.02 – 0.14
2. User acceptance	0.10	0.04 – 0.18
Economic		
▪ Low costs	0.14	0.10 – 0.17
Total	1.00	

Table 11.3 Result of the first workshop: selected sanitation and drainage options for unplanned areas in Ho Chi Minh City and attributed appropriateness scores (scale 1 – 100 (very inappropriate to very appropriate). Option numbers refer to the options list in chapter 5.

Selected system options	Option Number	Appropriateness score (Scale 1 -100) Average	Variation
1. Settled combined sewers without retention basins for reduction of combined sewer overflows	4E	65	56 – 74
2. Settled combined sewers with retention basins for reduction of combined sewer overflows	4F	50	28 – 71
3. Plain separate sewers	6A	49	28 – 74
4. Dry UD toilets + settled separate sewers (grey water)	10A	32	- [246]
5. Settled separate sewers with pump support	6E(P)	72	71-72

11.3.3 Methodological amendments on the basis of the first workshop

The participants found the SANCHIS approach for learning about drainage and sanitation options useful and innovative. They rapidly understood the assignments (Annex A.1.1) and

[246] Only one group has assessed this option so that no variation can be given.

the concept of assembling sanitation and drainage system options from the building blocks. The groups selected system options that were given in the list of chapter 5 but also new options. The order of the assignments as shown in table 11.1 turned out to be adequate. As performance assessment can be time-consuming, the participants were asked to limit the number of criteria to 8. They usually selected their criteria from the highest and second level in help-sheet (Annex A.11.2). It was useful that participants presented their objectives/criteria during a plenary session, so that they could exchange ideas about what they found characteristic of good drainage and sanitation solutions.

The workshop's duration of two half-days appeared to be too short for a thorough assessment of the performances. Participants judged various drainage and sanitation options quite differently (table 11.3) and also the weights of the criteria across groups were very different (table 11.2). A more detailed discussion and reporting could better reveal the backgrounds of the judgments. Striking was the different weights given to the criterion of *resource recovery*. This difference may have been due to differences of scope (solutions *for the world* versus solutions *for my city*) and timeframe (long term versus short term). Such differences in particular surfaced in the discussion about urine-diverting dry toilets. The participants needed to be convinced of the reliability and cost-effectiveness of innovative resource-saving and recovering solutions.
It was concluded that future SANCHIS workshops would at least require two days and that the participants would have to be asked to make a *strengths-weaknesses analysis* of their selected sanitation and drainage options in which they explicitly present the arguments for their options. It was expected, that this elucidates the groups' most important criteria and the way they assess the options' performance before they go into details during the construction of the performance matrix. For leading a SANCHIS workshop two facilitators turned out to be necessary: one to help the groups with the development and assessment of options (a sanitation and drainage expert), a second to control the process.

11.4 Second SANCHIS workshop in Ho Chi Minh City

11.4.1 Organization and objectives

This workshop took place in the initial stage of the Vietnamese partnership in the international ISSUE-2 programme (2007-2010) which aims at improved sanitation and solid-waste management for 5000 low-income households in Ho Chi Minh City in the framework of the Millennium Development Goals. This ISSUE-2 programme has been structured according to the principles of participatory multi-stakeholder planning, implementation and operation as proposed in chapter 2. A pivotal role is played by the consortia responsible for the execution of the programme in their intervention zone. These consortia unite local municipal governmental agencies of districts and wards, representatives of mass organizations (Youth Union and Women's Union), one or more support NGO's and other experts. The mass organizations in Vietnam in particular presented themselves as representatives of the households. The participants of the workshop were members of the consortia of the districts 6, Cu Chi and Nha Be of Ho Chi Minh City, and invited sanitation experts. The workshop was guided by two Vietnamese and two Dutch facilitators. The participants of the workshop were especially interested in the approaches of the ISSUE-2 programme and learning about new system options. As the ISSUE programme had just started, the consortia were not in the stage of taking decisions.

The workshop covered two days of which one and a half were dedicated to the SANCHIS method. During the first morning the consortia gave presentations about the sanitation and drainage problems in their districts. An excursion was organized to the intervention area in district 6. In the afternoon a plenary introduction of SANCHIS was given, after which the consortium groups worked on the assignment of formulating objectives for ISSUE-2 and criteria for good drainage and sanitation options. The second day started with the plenary introduction of assembling sanitation and drainage system options on the basis of the building blocks as explained in chapter 5. The consortium groups subsequently constructed their options, made a strengths - weaknesses analysis, filled out the performance matrix and weighted their criteria. On the basis of the work of the second morning the results of the appropriateness analysis were shown in a plenary session in the afternoon. An overview of the performed assignments is shown in Annex A.11.1.The workshop was completed with a discussion about further steps in the ISSUE-2 programme. The materials handed out to the participants were the various assignments, a list of criteria and the performance help-sheet (annexes A.11. 1 - 4).

11.4.2 Results

This subsection briefly describes the outcomes of the work in the three groups from the districts Cu Chi, Nha Be and district 6.

Cu Chi district in Ho Chi Minh City has (still) a rural nature. Much surface and groundwater in this district is polluted with pig and human wastes. The participants made a distinction between towns and rural areas. For rural villages integrated solutions were sought for wastewater of pig farms and individual households. Four technical systems were proposed as shown in table 11.4. For system judgement 10 criteria were used. The highest scores (86% and 88%) were attributed to the settled separate system (6E) and the on-site treatment of combined black water and pig dung in an anaerobic digester system. These two system options are shown in figure 11.1.

Possible weaknesses of the first system (table 11.4 #1) were the discharge of septic tank effluent to the subsoil as long as no communal wastewater-treatment plant is available. The second system is especially suited to rural zones in Cu Chi district with animal breeding and with sufficient space for fish ponds. This system so called VACB (garden-pond-pig-biogas) system that has a certain fame in Vietnam.

Table 11.4 Selected sanitation and drainage system options for Cu Chi district and attributed appropriateness scores (maximum = 100%).

System options	Option number	Appropriateness score (%)
1. Pour-flush toilet /settled separate sewer system	6E	86
2. Pour-flush toilet/ black water and pig dung to on-site anaerobic digester, reuse of digester effluent in fish pond; grey water to subsoil	New	88
3. Pour-flush toilet/ black water and pig dung by truck to off-site digester, reuse of digestate; grey water to subsoil	New	74
4. Dry anaerobic digestion toilet; off-site treatment of collected sludge; grey water to subsoil	New	66

Nha Be is a low-lying district in the South of Ho Chi Minh City with about 75,000 inhabitants where urbanization is in its starting phase. Up to recently a lack of usable groundwater has limited housing development. 60% of the households in the district lack a toilet, but many of them (more than 2,000) had loaned money for toilet construction. Sewerage had only been laid out along the main roads. During the workshop the team of Nha Be compared the appropriateness of pour-flush and cistern-flush toilets and of two pumped settled separate sewer systems for their district (table 11.5). The two drainage and sanitation system options 6E(P) and 6F(P) are sketched in figure 11.2. In both selections 4 criteria were used.
The workshop participants found the pour-flush toilet the better option by virtue of its lower investment cost and water consumption as compared to the cistern-flush toilet. They saw as disadvantage the limited reuse opportunities of the black water as compared to dry urine-diverting toilets.

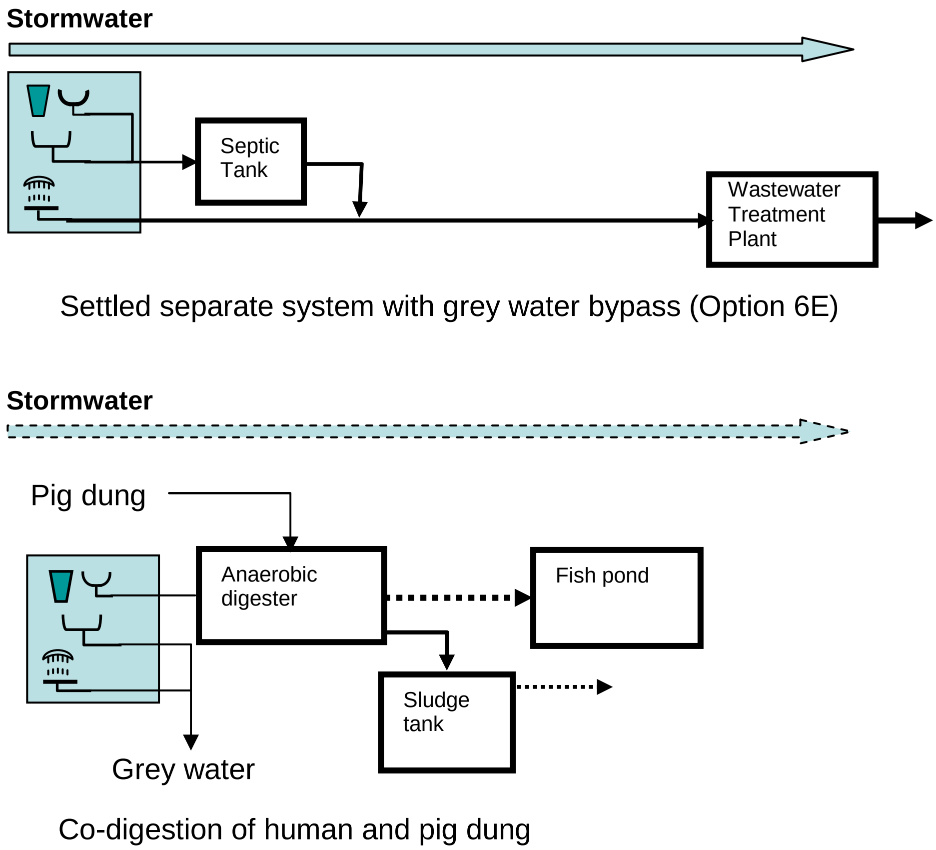
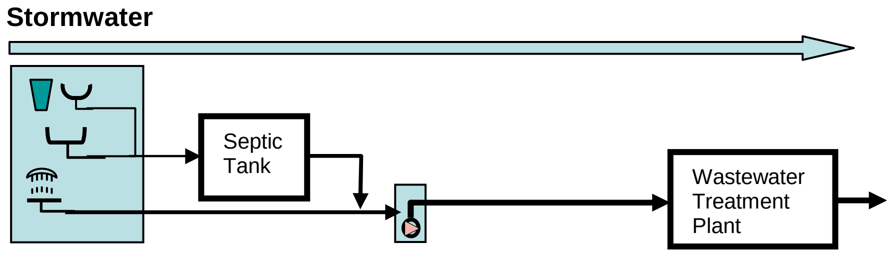
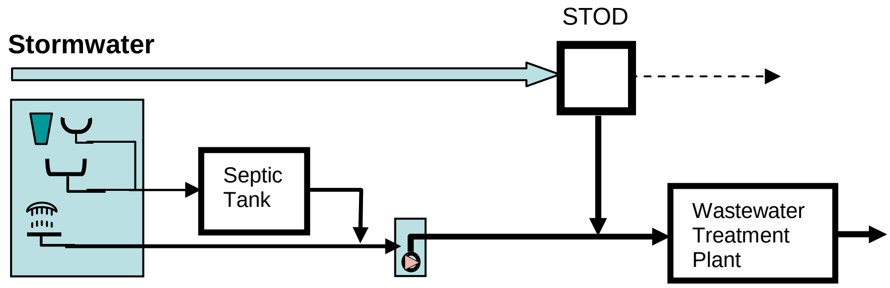


Figure 11.1 Drainage and sanitation system options selected for Cu Chi district in Ho Chi Minh City.

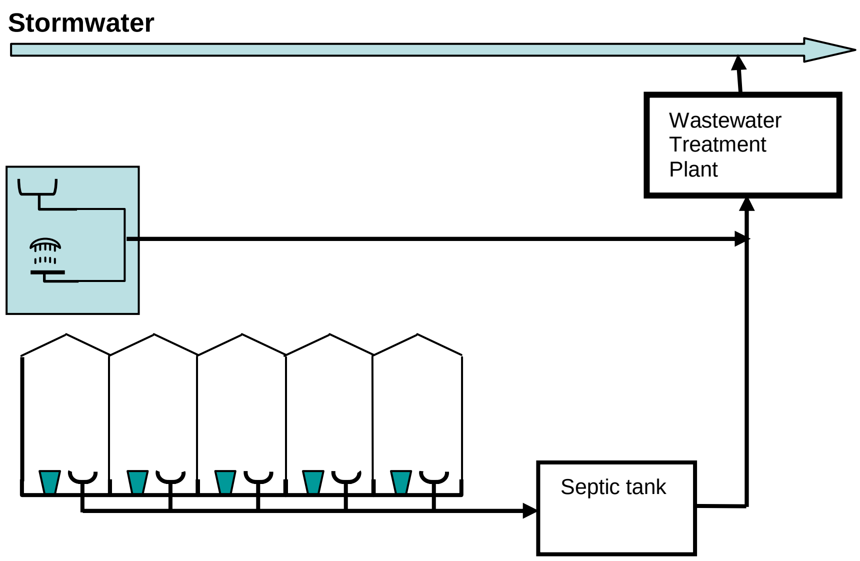


Settled separate system (pumped) (option 6E (P))



Improved settled separate system (pumped) (option 6F(P))

Figure 11.2 Drainage and sanitation system options selected for Nha Be district in Ho Chi Minh City.



Public toilets and settled separate sewerage (Option 6E + Public Toilets)

Figure 11.3 Drainage and sanitation system options selected for squatter areas in district 6 in Ho Chi Minh City.

The ISSUE- consortium in *district 6* addressed the lack of adequate toilets in 327 households living in poor houses along the banks of the Tan-Hoa Lo-Gom Canal. These households were using hanging-hole toilets above the canal, which is a cause of serious water pollution. The district wanted to put an end to this practice. Other households in the wards were equipped with pour-flush toilets and septic tanks whose effluent was discharged to an untreated combined sewer system. The options selected for the intervention areas of district 6 were settled combined and separate sewer systems in combination with public toilets (PT) (table 11.6). Four criteria were used in the judgment of the system options. The construction of individual toilets in the small houses along and above the canals is not practicable, so that the scores were low (50 and 47%). Lack of user acceptance was assumed to be a possible weakness of the public-toilet systems. The system option 6E + public toilets is shown in figure 11.3.

Table 11.6 Selected sanitation and drainage options for houses along canals in district 6 and attributed appropriateness scores (maximum = 100%) (PT = public toilets).

System options	Option number	Appropriateness score (%)
1. Pour-flush toilets/ settled combined sewer system with grey water bypass	4E	50
2. Public toilets/ settled combined sewer system	4E + PT	69
3. Pour-flush toilets/ settled separate sewer system with grey water bypass	6E	47
4. Public toilets/ settled separate sewer system with grey water bypass	6E + PT	65

11.4.3 Methodological amendments on the basis of the second workshop

Amendments to the SANCHIS method are proposed based on evaluation of the programme and its outcomes.

Evaluation of the programme

The second SANCHIS workshop differed from the first workshop (11.3) in that its participants were personally concerned to find solutions for their intervention areas. They could bring into the process their specific knowledge about the areas, which led to diverse specific technical solutions. During the assignments 1 and 2 of analysing drainage and sanitation issues and finding criteria for drainage and sanitation systems, the participants first exchanged their experiences with a wide range of environmental problems they were facing: lack of drinking water, polluted surface water, flooding, lack of toilets, lack of solid-waste collection, etc., and discussed the deeper causes of infrastructure problems (e.g. bad planning, lack of enforcement). This appeared to be a necessary first stage of the process, as participants wanted to share and explain their concerns and position with respect to the needs in their area before they started to design solutions for drainage and sanitation problems. For SANCHIS workshops whose participants are not yet focused on drainage and sanitation the first assignment of problem analysis could be subdivided into two stages, e.g.:

Stage 1a: Analysis of environmental infrastructure of the district (what are the problems, what are the causes, what is being done about them, what should be done?);

Stage 1b: Identification of drainage and sanitation problems of the district (causes, consequences of other infrastructure problems on drainage and sanitation, impacts of inadequate drainage and sanitation, for whom is it a problem and what is being done about them and what should be done?)
The time required for participants to become focused on sanitation and drainage problems probably depends on the responsibilities and expertise of the participants, and the way they have been able to prepare themselves before attending the workshop. A SANCHIS workshop with participants with various functions in a wide environmental field may need (much) more time for the shared problem analysis and narrowing down to drainage and sanitation than the 90 minutes reserved in the second workshop (Annex A.11.1).
The elaboration of a strengths - weaknesses analysis of the system options in the framework of assignment 4 (Annex A.11.1), turned out to be very useful, as it provided an opportunity to participants to inform each other about the options, to distinguish feasible and non-feasible options and construct the performance matrix.
The other assignments 3 and 5 until 8 could be executed in the times indicated in Annex A.11.1, though it seemed that assignments 6 and 8 during which criteria performances were ranked and weighted received less attention than the other assignments, probably due to fatigue at the end of the workshop and the fact that a real decision was not required.
Plenary introductions by the facilitators were indispensable, as they served to give direction to the group work in the first place. As the workshop setting did not offer the proper conditions for consultation of the offered hand-outs (Annexes 11.2-4), not much of this information could effectively play a role in the process. Accordingly, the oral exchange of information between group members and facilitators determined the group product. Plenary discussion about group products could, in principle, lead to corrections, but during this workshop too little time was used for a plenary in-depth discussion about the options.

Evaluation of the outcomes

In order to evaluate the assignment groups' needs and use of information the criterion performance scores estimated by the groups are compared with the scores calculated by the SANCHIS data-base. This comparison is made for the technology-specific sub-objective *Reduction of pollution* applied to the drainage and sanitation options 6E, 6E(P) and 6F(P) (figure 11.1-3). The results are listed in table 11.7. The scores given by the SANCHIS data-base were not used in the workshop.

Table 11.7 Estimated and calculated performance scores for the criterion Reduction of pollution during ISSUE-2 SANCHIS workshop (maximum score = 100).

Assignment group	Option	Drainage and sanitation system	Option score assessed in group assessments	Option score from SANCHIS data-base
District 6	6E	Settled separate sewer system	90	56
District Nha Be	6E(P)	Settled separate sewer system with pumping of wastewater	100	48
District Nha Be	6F(P)	Improved settled separate sewerage	80	68

According to the criteria list (Table 4.9; annex A.11.2) *Reduction of pollution* was assessed using 5 indicators of emission prevention, viz. COD (12) , N and P emissions to water (13), methane to atmosphere (14), malodours and insect vectors (15), and emissions to soil and groundwater (16). A calculation of the scores for the three drainage and sanitation systems from the SANCHIS data-base shows values that are considerably lower (from 48 to 68) than the scores obtained from the group assessments (from 80 to 100). This is due to the fact that the workshop participants only compared their own selected options, while the SANCHIS data base assesses a larger number of options of which some have much higher scores than the ones chosen in the workshop. The assessment of the group of the district of Nha Be yielded a lower pollution-reduction performance (score = 80) for the improved settled separate sewerage system (option 6F(P) than for the standard settled separate sewer system (option 6E(P) (score = 100). The SANCHIS calculation, on the contrary, showed a better score for the improved system, which seems logical as the aim of sending stormwater runoff to the wastewater-treatment plant is precisely to reduce the discharge of polluted runoff and accordingly reduce the pollution load to the receiving water. This 'deviating' group assessment would undoubtedly have been discovered and discussed with more time in the workshop for evaluation of the options or during a follow-up phase in which external experts would be consulted. The lower environmental performance score of the pumped settled separated system (6E(P), 48/100) in comparison with the gravity-flow settled separate system (6E, 56/100) is due to the higher methane emissions expected in pumped systems (subsection 6.4.8).

The validity of the performance matrices reached in SANCHIS workshops seemed to be contingent on the following factors: (1) the average level and variety of expertise among participants about drainage and sanitation options and their consequences in a certain location, (2) the effectiveness and duration of information exchange between participants, and 3) the way the participants' views are translated to the group result[247]. The reporter may have an above-average influence on the group work, since he or she may give a direction to the results at writing of the group report. The facilitators of the ISSUE-2 workshop observed that the level and variety of expertise in the consortium subgroups was not always adequate. In future SANCHIS workshops the composition of the participants' group should receive more explicit attention.

During this workshop the participants discussed and learned much about the drainage and sanitation infrastructure problems and their potential solutions. It became clear, that a trustworthy and broadly supported decision would have required a follow-up, during which there would be room for widening the number of considered options, deepening of the criteria performance analysis, the trading off between the options, and a broader stakeholder

[247] During the group work the criterion performance scores for system options may be obtained:

(1) by taking an average of the scores group members attribute individually after a certain exchange of opinions;
(2) by group consensus: one of the group members proposes a score based on certain argument and asks other members whether they agree or want to augment or diminish the value of the score.

The first method leads to results that more properly express all opinions in the group, as it depends less on the degree to which members feel to contribute to consensus-forming process.
On the other hand the first method may urge group members to give an opinion where they do not have one yet. In this workshop the second way was used.

participation. It was concluded that SANCHIS as a method in drainage and sanitation decision making should be applied in a *flexible* way with respect to setting, form, stakeholder involvement, and duration. The experiences of the first workshop (11. 3) led to improvements that were applied during the second workshop (11.4). On the basis of the second workshop additional amendments to SANCHIS could be recommended. These are detailed in the next section.

11.5 Recommendations for improvement of the SANCHIS method

On the basis of the two SANCHIS workshops reported above recommendations for further method improvement are proposed. These refer to the process initiative (11.5.1), the programme (11.5.2) and the provision of information (11.5.3).

11.5.1 Process initiative, participants and preparation

The facilitators of the two SANCHIS workshops learned that a SANCHIS process could be applied for decision preparation in various settings, e.g. in planning teams working on drainage and sanitation projects or master plans, in meetings of system users or in professional education. The initiative to run a SANCHIS process could originate from any actor group in an urban upgrading or building project, but most obviously from local government as prime responsible for urban infrastructure. The categories of participants and scope of the process are contingent to the setting. If systems are selected for implementation, all different types of stakeholders should be involved and input of all necessary information about the situation under study and about a variety of technical systems should be warranted. Participants should be well informed about the objectives and content of SANCHIS activities, such as a workshop, in order to create motivation, promote a proper preparation and obtain adequate results. The final decision maker should agree to adopt the outcome of the process, lest all effort be useless. As participants often have busy agendas, there is always the dilemma between the demands of the process and the time constraint of the participants. Where SANCHIS is applied for decision-making involving end-user groups (households) the organizers may opt for a delimitation of the scope and number of system options submitted for selection.

11.5.2 Programme

If municipal planning teams apply SANCHIS in a system selection process, opportunities for judgment by stakeholders outside the group of direct participants should be included in the programme. The entire process could be structured as shown in figure 11.4.

The SANCHIS process evaluated in this chapter covered the first two stages of process, namely (1) initiative and preparation and (2) the first stakeholders workshop, but it did not include the evaluation of options by external parties and the decision making proper.

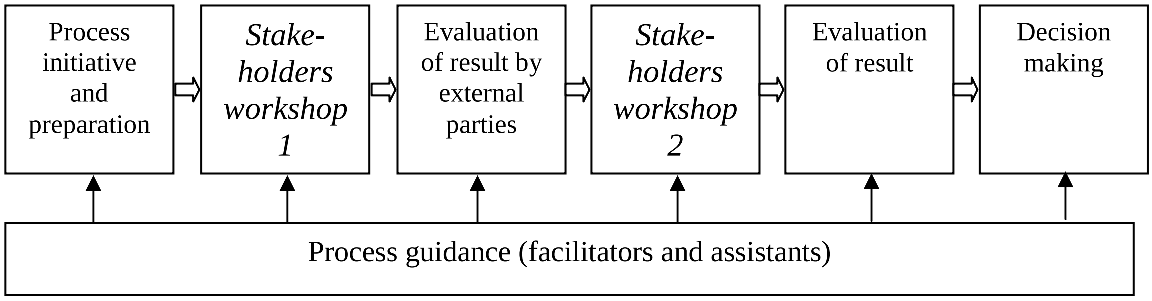


Figure 11.4 Recommended structure of the SANCHIS process

More than the workshops in Ho Chi Minh City described above, a decision process envisaged in figure 11.4. would provide opportunities of input by various stakeholders and external experts according to need, it would give flexibility with regard to the options and criteria under study, the input and exchange of information, and the duration of the process. At the second workshop the system options that really matter would have to be assessed with more precision (e.g. regarding costs) than during the first workshop. Accordingly, the process would be more flexible. A skilled guidance of the process should avoid the application of infrastructure solutions that would conflict with decisions taken at a higher level, unnecessary loss of time and costs. If the emphasis is on learning about options and their strengths and weaknesses a SANCHIS programme could reach its goal by the first two stages only.

11.5.3 Information exchange

In a learning and decision-making process as indicated in figure 11.4 there would have to be ample opportunities for input and exchange of information at all stages in order to reach appropriate drainage and sanitation solutions, supported by stakeholders' commitment.
At the start of the decision-making process potential participants have to be convinced about the importance of embarking on a multi-stakeholder drainage and sanitation selection process. This requires explanation about the objectives and procedure of the SANCHIS process.
During the workshops plenary introductions by the facilitators should instruct about the SANCHIS steps and the use of the available written material. This material should be understandable at a glance, since little time for reading is available during the workshops.
The help-sheets of Annexes A.11.2 and 3 handed out during the workshops appeared sufficiently clear and understandable, but the decision aid A.11.4 had to be improved. The result is shown in chapter 6, section 6.7.
During the work in assignment groups the facilitators play an active role in eliciting arguments pro and contra certain system options; they also encourage to look at solutions that could be judged unfeasible at first sight, in order to avoid selection of just business-as-usual options. SANCHIS workshops have shown to generate new drainage and sanitation system options, such as two of the five system options shown in figure 11.1-3. Consequently, the plenary introductions and help-sheets will not always suffice to provide the required performance information. This is another argument in favour of having all selected options judged by experts during and after the workshop. Especially, their feasibility in the situation under study should be co-assessed. These judgments can be brought back to the assignment group for a final round of options selection during the second workshop (figure 11.4). The stages after the first workshop may serve to deepen the understanding of the consequences of the choices made, to add, if needed, new system options, and reiterate the process of options

assessment and trading off in order to enhance the chance of reaching the most appropriate drainage and sanitation solution for the situation under study.

11.6 Discussion and conclusions

The conclusions gained during the two workshops described above are presented here subdivided into an overview of strengths, issues and limitations (11.6.1) and the perspectives of the SANCHIS method (11.6.2).

11.6.1 Strengths, issues and limitations of the SANCHIS method

The SANCHIS method was designed to support a participatory process in public decision making about urban drainage and sanitation infrastructure in developing countries. Therefore, it is valid to compare the experienced strengths and weaknesses of SANCHIS with the general inventory of strengths and weaknesses of citizen's participation in public decision making as given in section 3.4, table 3.8. With regard to *weaknesses* a distinction is made between weaknesses experienced during the two workshops discussed here and limitations of the method. The first are called 'issues' and could probably be overcome by process improvements. Limitations are weaknesses more fundamental to all participatory decision-making processes.

The most important strengths and issues experienced during the two workshops are listed in table 11.8.

Table 11.8 Strengths and issues experienced during the SANCHIS workshops.

Strengths	Issues
The strengths of a bottom-up approach are demonstrated by involving more than the obvious stakeholders in planning and decision-making about infrastructure.	It has proven difficult to determine at an early stage who should be involved in the process. Incomplete involvement of relevant stakeholders could lead to opposition against selected options after decisions have been taken.
Obtaining a shared and deepened view among stakeholders of the problem to be addressed and its solutions.	The supply and exchange of information about options during the construction of the performance matrix proved insufficient.
Fast learning about sanitation objectives and a wide range of drainage and sanitation options.	
Generation of new options for situation under study based on the building blocks.	
Enhanced commitment for realizing new infrastructure based on a better vision of the possibilities.	

The strengths of fast learning, generation of new options, clarification of different views, bridging of gaps between scientifically defined environmental problems and practice, and establishment of commitment among stakeholders, mentioned in table 3.8, were encountered during the SANCHIS workshops as well. SANCHIS workshops matched well with the bottom-up approach in environmental infrastructure planning of the ISSUE-2 sanitation programme. Participants considered this as particularly important in Vietnam where up to now very little experience with this type of decision making has been gained. It has not be evaluated yet, whether the process of ISSUE-2 in which SANCHIS was applied has resulted in ‘better’ interventions. The proposed solution of public toilets for district 6 is being implemented at the moment of writing this text and will be evaluated after completion of this thesis. As SANCHIS workshops proved to be strong in making their participants understand about a wide spectrum of drainage and sanitation options, they can be recommended as well as an excellent tool in environmental technology education.

The issue of involvement of all relevant stakeholders is important (table 11.8). E.g.: after the representatives of district 6 had chosen their most appropriate system options during the ISSUE-2 SANCHIS workshop, these options were challenged by the foreign project management of the ISSUE-2 programme which had not attended the workshop. A controversy rose about the environmental sustainability of the chosen communal toilets that discharge to the public sewers. This controversy could have been addressed effectively, if the foreign project staff would have participated in the first workshop or in a follow-up stage as proposed above during which new stakeholders could have given their input.
The author was aware of the fact that the ISSUE-2 workshop reported here took place at a very early stage of the ISSUE-2 programme in which not all stakeholders had been properly identified and some of those who participated did not feel sure about their role in the process.
An improved organization of the process could mitigate several of the weaknesses of participatory public decision making listed in table 3.8 (chapter 3). This could hold for difficulties related to involvement and preparation of participants and stakeholders and the status of the results within the overall governmental political process. The cost of a participatory process in terms of time and money should be balanced against the importance of involving certain groups or individuals. Other weaknesses, or rather limitations, however, are fundamental to decision-making processes in which several stakeholders (e.g. lower government, community organizations, end-users) are given the responsibility and the power to direct decisions. Although multi-stakeholder decision making carries the promise of legitimate and effective policies and interventions through taking into account more knowledge, opinions and interests, there is no guarantee that the outcomes will always be cost-effective and sustainable solutions. Dominant stakeholders, driven by particular interests, could be overrule others even if their arguments are wrongful. Strong controversies either among the participating stakeholders or between the stakeholders and higher governmental organizations could stretch or stall the process. After all, prerequisites of a successful participatory process are the willingness of all participants to accept the rules of democratic decision making (decision by majority, persuasion by valid arguments, open and respectful communication) and an adequate level of relevant knowledge. These prerequisites seemed to be fulfilled sufficiently during the two SANCHIS workshops in Vietnam, but in general need explicit attention during the preparation of a workshop.

11.6.2 Perspectives of SANCHIS

In answer to shortcomings of centralised drainage and sanitation infrastructure, especially strongly felt in developing cities, four transformation processes in infrastructure development have emerged that result in diverse arrangements in planning and management and a mixed infrastructure encompassing both centralized and decentralized hard-ware. The mixture could be more environmentally sustainable than centralised infrastructure (chapter 2 and 8). Seven normative principles were found that accompany these transformations (chapter 2). A common factor in the realization of these principles is *stakeholder cooperation*, which could contribute significantly to: a) planning of infrastructure based on outcomes of an broadly informed analysis of the situation under study; b) openness to new technologies, instead of sticking to business-as-usual solutions; c) an infrastructure that is accessible to all, not excluding the poor; d) realization of an enabling environment to actors in infrastructure provision and use; e) drawing benefits from the resources of all involved partners, and f) financial transparency.

On the basis of the experiences gained with the drainage and sanitation workshops presented in this chapter the SANCHIS process could be judged as a highly promising method in participatory multi-stakeholder drainage and sanitation planning, and could consequently become an essential component of urban sustainable water management. More experiences with SANCHIS should be gained, especially with its application in a full decision-making process and in projects of different scales. Application of the SANCHIS process could lead to development of a tailor-made drainage and sanitation infrastructure adapted to the requirements and possibilities of local situations and users. The found solutions could be more effective and less expensive than one-size-fits-all solutions laid out indiscriminately over large upgrading zones. A demand for SANCHIS processes is expected in particular where the choice of new drainage and sanitation infrastructure is not obvious and where there are stakeholders with different situations, ideas and interests. Under such conditions various drainage and sanitation solutions could be appropriate and a common ground for action has to be found. This is the situation in the unplanned areas of Ho Chi Minh City.

Appendix of chapter 11 Handouts for SANCHIS workshops

The SANCHIS process includes workshops where stakeholders prepare and take decisions about drainage and sanitation infrastructure. The workshop programme includes introductions by facilitators, group assignments and plenary presentations of group work followed by discussion. The following support material was used in the SANCHIS workshops.

- Group assignments for two-days workshop (annex A.11.1);
- SANCHIS list of criteria and factors and schematic overview of criteria (annex A.11.2);
- Building blocks and performance help-sheets (annex A.11.3);
- Decision-aid (annex A.11.4).

These documents are presented below as annexes.

A. 11. 1 Groups Assignments

The group assignments, their required products and approximated time need are listed in table A.11.1. The duration is an indicative value which may vary with the nature of the workshop.

#	Group Assignments	Products	Duration (min)
	Day 1		
1	Analysis of drainage and sanitation problems of the intervention zone	Shared problem analysis in drainage and sanitation	90
2	Identifying objectives/criteria for improved infrastructure (using objectives and criteria help-sheet (Annexe A.11.2.)	List of criteria for options assessment	45
3	Generating drainage and sanitation options using the building blocks (using building blocks helpsheet (Annexe A.11.3)	List of systems options	60
4	Screening feasible from unfeasible options using strengths - weakness analysis and identification of restrictive factors (Annexe A.11.4)	List of feasible options	60
	Day 2		
5	Determining the performance of the feasible options with regard to the technology-specific criteria	Performance matrix	60
6	Selection of best options with respect to technology-specific criteria (ranking, weighting and overall appropriateness calculation)	Appropriateness index based on technology-specific criteria	60
7	Determining the performance of the feasible options with regard to the site-specific criteria	Performance matrix	60
8	Selection of best options with respect to site-specific criteria (ranking, weighting and overall appropriateness calculation)	Appropriateness index based on site- specific criteria	45
9	Drawing conclusions and taking the decision about the appropriate options	Decision about best system option(s)	45
10	Evaluation of workshop	Lessons learned and recommendations for follow-up	45

A.11. 2 SANCHIS list of criteria and factors that affect the system performance

TECHNOLOGY-SPECIFIC CRITERIA

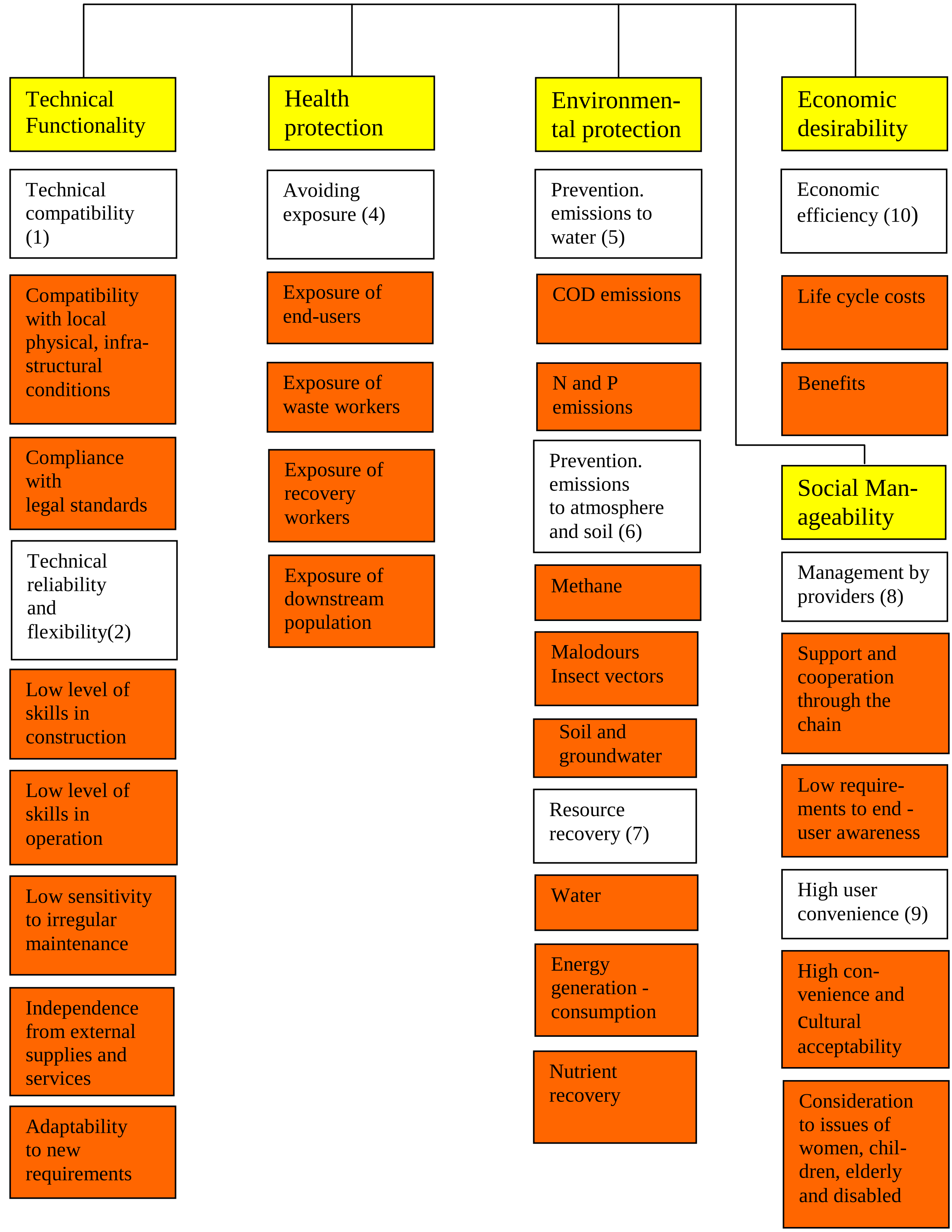
TECHNICAL FUNCTIONALITY

	CRITERIA	**Factors that affect the performance**
1	COMPATIBILITY WITH LOCAL PHYSICAL AND INFRASTRUCTURAL CONDITIONS	Various restrictive factors
2	COMPLIANCE WITH LOCAL LEGAL STANDARDS	Legal requirements can be a restrictive factor
3	LOW LEVEL OF SKILLS NEEDED IN CONSTRUCTION	High skills are needed in options that need technical design, project planning, mechanical construction equipment, involvement of many suppliers
4	LOW LEVEL OF SKILLS NEEDED IN OPERATION	High skills are needed in options with electro-mechanical and computerized equipment
5	LOW SENSITIVITY TO IRREGULAR MAINTENANCE	Options that include parts that need regular maintenance (UD flush toilets, cartage systems (by truck), pumping stations, mechanical wastewater treatment) are less reliable where regular maintenance is not guaranteed.
6	PREVENT FAILURES DUE DEPENDENCE ON EXTERNAL SUPPLIES AND SERVICES	Options that depend on technical energy or supply of chemicals and spare parts (pumping and mechanical treatment of wastewater) may be less reliable in areas where supply and services often fail or funds are not secure
7	FLEXIBILITY: EASE OF ADAPTATION TO NEW REQUIREMENTS	On-site and community-scale systems are more flexible to new requirements than large-scale transport, treatment and reuse systems
HEALTH PROTECTION		
8	PREVENTION OF EXPOSURE OF END-USERS	Options where end-users are exposed on cleaning such urine diverting dehydrating toilets may get a low score
9	PREVENTION OF EXPOSURE OF WASTE WORKERS	Options where waste workers are exposed on cleaning and transport of excreta may get a low score
10	PREVENTION OF EXPOSURE DURING REUSE	Options where contaminated water or faecal sludge comes in contact with agricultural workers may get a low score
11	PREVENTION OF EXPOSURE OF DOWNSTREAM POPULATION	Options where people may come into contact with contaminated surface water or vegetables irrigated with contaminated water may get a low score

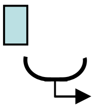
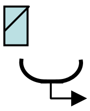
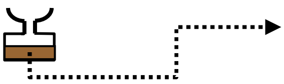
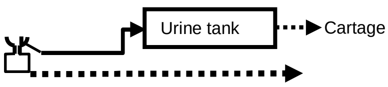
TECHNOLOGY-SPECIFIC CRITERIA (CONTINUED)		
ENVIRONMENTAL SUSTAINABILITY		
	CRITERIA	**Factors that affect the performance**
PREVENTION OF EMISSIONS		
12	PREVENTION OF EMISSIONS OF COD DUE TO STORMWATER RUNOFF AND SEWAGE	Options with unmitigated combined sewer overflows and discharge of untreated stormwater runoff get low score
13	PREVENTION OF EMISSIONS OF N AND P DUE TO STORMWATER RUNOFF AND SEWAGE	N and P emission can be prevented by (1) direct effluent reuse in agriculture and aquaculture, (2) separated urine and faeces collection and reuse and (3) tertiary wastewater treatment
14	PREVENTION OF EMISSIONS OF METHANE	Options with anaerobic treatment technologies, where the methane is not reused or flared, emit strong greenhouse gas methane. This gives a negative score
15	PREVENTION OF ODOUR AND INSECT NUISANCE	Storage of sewage and stormwater may cause malodours and insect nuisance
16	PREVENTION OF EMISSIONS TO SOIL AND GROUNDWATER	On-site soakage pits and improperly constructed septic tanks and sewer systems may cause pollution of soil and groundwater
RECOVERY OF RESOURCES		
17	RECOVERY OF EFFLUENT	Separate collection and treatment of black- and grey water yields grey water with a low concentration of salts and pathogens. Effluent from grey water treatment is more suitable for irrigation than treated sewage.
18	ENERGY GENERATION – CONSUMPTION	Energy recovery is highest in systems with separate collection and anaerobic treatment of black water. Energy recovery is also reasonable where biogas is produced from sewage sludge in central WWTPs. All building blocks, such as septic tanks, that keep organic matter from the WWTP have a reduced score.
19	RECOVERY OF NUTRIENTS	Recovery can be high (highest score) in options where excreta are directly reused. The faecal matter that contains the nutrients is collected, treated and reused. Recovery is less in centralized treatment plants, especially where the P-rich sludge is too contaminated to be used in agriculture.

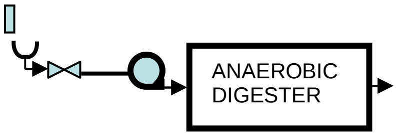
SITE-SPECIFIC CRITERIA		
SOCIAL MANAGEABILITY		
	CRITERIA	**Factors that affect the performance**
20	INSTITUTIONAL SUPPORT AND COOPERATION THROUGH THE CHAIN	Options that need much support and cooperation are more difficult to manage (low score). Where reuse of water and nutrients is practiced stakeholders have to cooperate.
21	LOW REQUIREMENTS WITH RESPECT TO END-USER AWARENESS	Options that need much end-user awareness with respect to use and maintenance are more difficult to manage (low score).
22	HIGH CONVENIENCE AND CULTURAL ACCEPTABILITY	Options that are convenient and acceptable to end users are easy to manage (high score). Flush toilets score high.
23	CONSIDERATION TO ISSUES OF WOMEN, CHILDREN, ELDERLY AND DISABLED	Options that consider issues of women, children, elderly and disabled are better accepted and easy to manage (high score)
ECONOMIC DESIRABILITY		
24	LOW LIFE CYCLE COSTS	Costs are low for on-site treatment systems Costs are relatively high for options that use pumped, vacuum and cartage collection, rainwater treatment and storage basins to reduce combined sewer overflows. Separate sewers are more expensive than combined sewers
25	HIGH BENEFITS FROM REUSE	Benefits are to be expected from options that save and recover water, nutrients and energy.

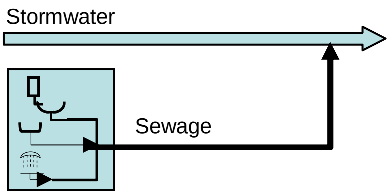
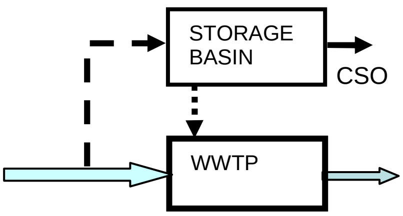
A.11.2 (continued) Schematic overview of objectives and criteria for drainage and sanitation systems' assessment

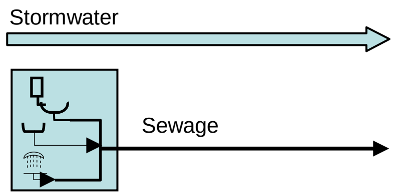
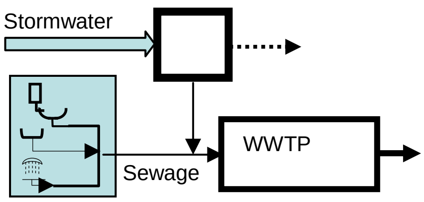
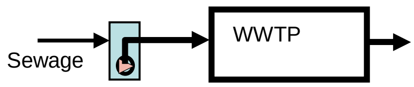


A.11.3 Building blocks performance help-sheet for SANCHIS drainage and sanitation workshop

BUILDING BLOCK	WHY APPLY IT?	POSSIBLE DISADVANTAGES
TOILET TYPES		
POUR-FLUSH TOILET 	To have a basic flush toilet at low cost with low water consumption (10 l/cap/d)	Users may prefer higher convenience
CISTERN-FLUSH TOILET 	To have a convenient flush toilet with a water consumption of about 40 l/cap.d	High water consumption Black water diluted, therefore much energy needed for treatment
DUAL-FLUSH CISTERN FLUSH TOILET 	This toilet has a reduced flush water consumption in comparison to the regular cistern-flush toilet (25 - 30 l/cap/day)	
URINE-DIVERTING FLUSH TOILET 	To obtain separation of urine and faeces. By collection of urine nitrogen and phosphorus can be recovered. Water consumption is about 6 l/cap.d.	More expensive than regular flush toilets. Possible lack of user acceptance; maintenance of valve. Urine storage, transport and reuse must be organized
ANAEROBIC DRY TOILET (ON-SITE ONLY) 	To save flush water, recover nutrients and avoid pollution of groundwater. In communal toilet blocks energy could be recovered. Experiments in Tanzania.	Expensive cartage and treatment of slurry.
URINE-DIVERTING DRY TOILET 	To save flush water, reuse urine and faeces for nutrient recovery. It is a simple, cheap and reuse-oriented system.	Cartage of urine and dried faecal matter to site of treatment and reuse

BUILDING BLOCKS (CONTINUED)	WHY APPLY IT?	POSSIBLE DISADVANTAGES
VACUUM TOILET 	To save flush water and recover nutrients and energy Reuse of grey water	High tech, high investment costs, treatment and reuse of black water in an experimental stage.

SEWERS AND WASTEWATER TREATMENT BUILDING BLOCKS	WHY APPLY IT?	POSSIBLE DISADVANTAGES
SEPTIC TANK 	To achieve on-site removal of solids. This technique prevents clogging of pipes and facilitates use of small-bore sewers at low gradient and reduced costs.	Investment costs. Uncertain treatment performance Escape of methane to atmosphere: Green House Gas!
COMBINED SEWER SYSTEM 	Enables simple connection of households to stormwater pipes. Especially suitable in urban areas with moderate rainfall intensity.	Environmental pollution due to overflows and reduced efficiency of WWTP at high rainfall.
ENHANCED STORAGE CAPACITY IN COMBINED SEWER SYSTEM 	This technique improves the environmental performance of the combined sewer systems by increasing the storage capacity of the sewer system and reducing the pollutant load from combined stormwater overflows (CSO) to surface water.	Extra costs, need of space to build reservoir, open reservoirs may cause insect nuisance

SEWERS AND WASTEWATER TREATMENT BUILDING BLOCKS	WHY APPLY IT?	POSSIBLE DISADVANTAGES
SEPARATE SEWER SYSTEM 	Improved efficiency and management of wastewater treatment plant as no or only little rainwater is discharged to treatment plant	High costs. Environmental pollution due discharge of untreated stormwater. Wrong connections to stormwater pipes cause wastewater emissions.
IMPROVED SEPARATE SEWER SYSTEM 	Stormwater overflows only at high rainfalls. High efficiency and management of wastewater treatment plant. Strong reduction of stormwater pollutants discharge to surface water.	More expensive than combined and plain separate systems.
SEWAGE PUMPING 	To guarantee transport where terrain slope is insufficient for gravity transport	Additional costs of investment and maintenance.

A.11.4 Decision aid

The decision aid defines unfeasible and unlikely drainage and sanitation systems in relationship with the conditions of the intervention zone.

DECISION AID TO DETERMINE FEASIBILITY OF DRAINAGE AND SANITATION SYSTEMS IN YOUR INTERVENTION ZONE

NR	RESTRICTIVE FACTOR	CONDITIONS	SUGGESTIONS
1	DOMESTIC WATER CONSUMPTION	Hand carried, low consumption	Flush toilets and piped sewers are unfeasible where water supply/consumption is limited. At very low water consumption dry toilet systems are most adequate.
		Piped water, high consumption	Dry toilet systems and communal toilets are unlikely.
2	BUILDING DENSITY	Low density/ low water consumption	System options with flush toilets, transport and off-site treatment of wastewater are unlikely since there is only little water to handle
		Low density/ high water consumption	Dry toilet options are unlikely. Improved separate sewer systems are unlikely since stormwater runoff is expected to be little polluted
		High density/ low water consumption	System options based on flush toilets are unfeasible. If space is sufficient, household dry toilet systems are most likely. If space is insufficient communal toilets are required
		High density/ high water consumption	Household on-site wastewater-treatment options are unlikely due to lack of space
3	STORMWATER RUNOFF QUALITY	Low	In city areas whose stormwater runoff contains much waste polluted overflows of combined and separate sewers to surface water should be minimized. Here, improved combined and separate systems are preferred.
		High	Stormwater runoff can be discharged to surface water without causing pollution. Improved separate systems are unlikely
4	RAINFALL INTENSITY	Very low	Combined sewer systems are unfeasible since they will get clogged during long dry periods
		Low and moderate	No unfeasible systems
		High	High rainfall intensity and combined sewer systems may lead to high overflow frequency and overloading of treatment systems; separate sewer systems are preferred under these conditions
5	TOPOGRAPHY	Low gradients	If transport distances are long and no local treatment plant is possible, pumping of sewage may be needed.
		High gradients (mountainous)	Cartage systems may cause problems of access in mountainous areas.
6	COMPLIANCE WITH LEGAL FRAMEWORK	Alternatives not supported by or complying with local regulations and policies are not feasible. (E.g. in Vietnam the on-site septic tank is legally required). Options without septic tanks are unfeasible.	

CHAPTER 12 SUMMARY

12.1 Introduction

A significant part of the population in developing countries, in particular the poor living in slums and other unplanned urban areas, has no access to adequate drainage and sanitation provisions with grave consequences to health and living conditions. This thesis takes an analysis of the causes and consequences of that provision deficit as point of departure and seeks more effective mechanisms for inclusive and environmentally sustainable drainage and sanitation implementation in developing countries. This occurs at two levels. Firstly, there is the level of the developing cities in general (chapter 2 until 7), and secondly the level of Ho Chi Minh City, Vietnam (chapters 8 until 11). The case-study of Ho Chi Minh City is meant as a source of deepened insight, and as a place where new approaches can be developed and tested in a concrete programme of solving drainage and sanitation problems in unplanned and underprivileged areas. As the mentioned deficit is analyzed as rooted in a top-down approach, with a too limited involvement of the users of systems, a more effective approach is sought in a bigger contribution of communities to project planning, implementation and operation, without, however, denying the important role of governmental agencies. The main contribution of this thesis to a multi-stakeholder approach is SANCHIS (Sanitation Choice Involving Stakeholders), a method for participatory technology selection in the domain of drainage and sanitation. This chapter 12 summarizes step-by-step the answers to the research questions raised in chapter 1.

12.2 Synopsis

Chapter 2 investigates the question: *what are the main challenges and practiced approaches to solutions in urban water management in The South?*
Urban water management, especially drainage of stormwater runoff and sanitation, can be considered as a public good with an obvious main role for governmental agencies in its regulation and implementation. Without losing sight on the historic successes of governmental management in now developed countries in the North, the top-down approach to infrastructure provision is analyzed as incapable of efficiently reaching the masses of poor people in developing countries. New implementation arrangements in which market parties and community-based networks complement, or even replace, the role of the governmental agencies have been proposed to obtain the breakthrough intended by the United Nations Millennium Development Goals (McGranahan et al., 2001; EAWAG, 2005; WSP, 2009). Lack of access for the poor is not the only deficiency of the currently implemented drainage and sanitation infrastructure. Many new opportunities have been identified to improve its environmental sustainability. In several countries innovative technical systems are researched and introduced to improve drainage and sanitation infrastructure with respect to emission reduction, and saving and recovery of water, nutrients and energy. Other countries are expected to follow in this trail. In agreement with the hopeful expectations about multi-stakeholder approaches and the quest for environmental sustainability, chapter 2 postulates four transformations in the practice of drainage and sanitation improvement: (1) a stronger involvement of users, community organizations and the private sector in planning, decision-making and implementation of infrastructure, (2) a more decentralized organization in infrastructure management, (3) saving resources and reducing emissions through closing

material cycles, and (4) the acceptance of on-site and community-based drainage and sanitation technologies as legitimate alternatives in urban technological mixes. The affirmative stance throughout this thesis towards a strengthened role of community action in infrastructure implementation is based among other things on the anticipated beneficial effects of community involvement, viz. strengthening of learning and reflection, greater transparency in planning and decision making, greater overall stakeholder commitment and capacity building with a spill-over effect to other community-building actions. The proposed transformations imply new institutional arrangements, including methods to support a participatory drainage and sanitation-system selection process. The development of such a method, named SANCHIS, is described in the chapters 3 to 7. An essential question associated with the introduced approach directed at participation of various stakeholders in planning and decision making processes is whether it leads to more effective and legitimate decisions than if governmental agencies would act without, or with much less, input from stakeholders. The process and outcomes of a participatory approach to drainage and sanitation improvement in Ho Chi Minh City are assessed in chapter 11.

The leading research question in the development of the SANCHIS method in chapter 3 was: *What would be an adequate method for planning and selection of appropriate and sustainable drainage and sanitation systems?*
First technology selection is defined as part of a multi-stage planning process: the intervention cycle. Taking literature on multi-criteria decision analysis as point of departure the selection process is conceived as consisting of the five steps of problem analysis, defining objectives and criteria, looking for system options, finding out the consequences or performance of these options and trading off between the strengths and weaknesses of the options (Hammond et al., 1999). These steps are discussed and a new methodology is proposed for their application in drainage and sanitation selection. Important distinctions are technology-specific and site-specific performance measurement, and screening and comparison of options. The SMARTS procedure (Edwards and Barron, 1994) was selected for trading-off by virtue of its user-friendliness, ease of visualizing results and instructiveness (Olson, 1995). The proposed multi-criteria method is coupled with a method of participatory decision making, since from such a process important advantages of joint problem clarification, fast learning, establishment of commitment and better interventions may be expected. Finally, other comparable decision-support methods are assessed, namely SANEX©, the Philippine Sanitation Sourcebook, the NETSSAF flowstream approach and the EAWAG Compendium of Sanitation Systems and Technologies (Loetscher, 1999; PHSSDA, 2007; Zurbruegg and Tilley, 2007; Tilley et al., 2008). With the exception of SANEX©, these decision support aids have been developed recently, simultaneously with SANCHIS. As compared to these decision-support systems the SANCHIS method puts more emphasis on urban drainage and sanitation and less on rural solutions, and more on drainage of stormwater and on innovative reuse-oriented solutions.

The selection of a most appropriate drainage and sanitation system out of a group of possible options by means of multi-criteria decision analysis requires criteria with which systems can be assessed and compared. Hence, the leading research question of chapter 4 is: *What are adequate criteria for assessment of the appropriateness and sustainability of drainage and sanitation systems?* These criteria were selected based on literature and the author's experience. During the selection much care has been taken to avoid overlapping of criteria and to formulate suitable indicators for the measurement of criterion attainment. The results are lists of 2 site-specific *screening* criteria, 23 criteria for technology-specific comparison and a tentative list of 11 site-specific criteria related to stakeholder acceptance. The criteria were grouped under the principal objectives of technical functionality, protection of health, environmental protection and material resources conservation, social manageability and economic desirability. While the performance of drainage and sanitation systems with regard to technology-specific criteria is to a high degree independent on the site of implementation, the performance with regard to site-specific criteria depends entirely on the circumstances in which a system is implemented. Accordingly, the technology-specific criteria performance can be measured by means of objective indicators, while the site-specific criteria performance is determined in the setting of a dialogue of local experts and other stakeholders. Chapter 10 demonstrates such an objective performance measurement. Both technology and site-specific criteria were applied in stakeholder workshops in Ho Chi Minh City in the selection of appropriate drainage and sanitation systems for different districts in that city (chapter 11).

The heart of the SANCHIS method is the elaboration by stakeholders of feasible drainage and sanitation system options for the intervention zone under study. In order to support this elaboration in the context of participatory decision making or professional training a list of system options was developed in Chapter 5 under the research question: *Which are the technological system options in drainage and sanitation applicable in cities in developing countries?* These system options are defined as an assembly of technologies for 5 different functions: toilets, on-site storage and treatment, transport, off-site treatment and reuse/disposal. As these system options had to be visualized in a simple way, a method of sketching was developed assembling the systems with tokens that symbolize different technologies (building blocks). The list composed in chapter 5 consists of 58 drainage and sanitation systems, or material chains, subdivided into 12 groups of on-site, community-based off-site and central off-site systems. The system options include 6 different toilet types: 2 dry toilets, 2 flush toilets and 2 toilets types that separate waste streams at source. Special emphasis is laid on reuse-oriented systems with source separation of wastewater streams.
While in the classification of chapter 5 system options are grouped according to the various possibilities of collecting source streams, the author has considered a classification based on ‘reversed’ material chains (Grendelman and Huibers, 2010). The reversed chain approach puts the reuse of end products of sanitation chains, such as irrigation water or compost, center stage and subsequently orders system options according to different reutilization possibilities (Mara et al., 2007). The strength of this approach is drawing all attention and creativity to closing material cycles. As this approach, however, did not deliver a suitable principle of ordering all systems and seemed much less useful to drainage and sanitation system choice in the framework of the SANCHIS processes in Vietnam, it was abandoned.

The assessment of drainage and sanitation systems is carried out through performance determination of the building blocks that constitute the system (toilets, on-site treatment, etc.) and aggregation of these performances into a total system judgment. The performances of the drainage and sanitation technologies are elaborated in chapters 6 and 7 using the two research questions:
What are the technical, health-related and environmental performances and what are the factors that restrict the application of the technologies that together form the drainage and sanitation options described in chapter 5?

What are the investment and operational costs of the technologies that together form the drainage and sanitation systems described in chapter 5?
The judgment about technologies for a concrete intervention area includes two steps: the *screening* to distinguish between feasible and unfeasible technologies and the comparison of feasible technologies. Unfeasibility, which indicates that the use of a technology in the situation under study should be seriously discouraged, is determined by means of restrictive factors. On the basis of restrictive factors screening aids have been developed for the 12 drainage and sanitation groups distinguished in chapter 5 and for sewage-treatment options. For the *comparison* of system options both site-specific and technology-specific and criteria from chapter 4 are used. Chapters 6 and 7 present a unique review of a vast amount of information that enables the assessor to compare criterion performances of drainage and sanitation technologies and systems, without having to dive deep into other literature. The literature research for chapter 6 revealed several promising new wastewater-treatment technologies for developing countries, such as the UASB septic tank, the baffled anaerobic septic tank, subsurface-flow constructed wetlands for raw sewage, mobile-bed bioreactors and down-flow hanging sponges towers. Chapter 7 integrates the data of the costs of the building blocks of drainage and sanitation systems into an estimation of overall system costs. The chapter concludes with the following ranking from least to most expensive classes of system options: household on-site systems with dry toilets < household on-site system with flush toilets < communal (central) off-site treatment systems serving households with regular flush toilets, urine-diverting flush toilets and dry toilets < small-community conventional and reuse-oriented off-site systems with two until four separated wastewater streams. System options with urine-diverting flush toilets for recovery of nutrients appear to be only slightly more expensive than system options with regular toilet systems. The comparison of primary plus secondary wastewater-treatment technologies with a small spatial footprint for tropical countries shows that UASB reactors, UASB reactors plus facultative ponds and UASB-reactors plus trickling filters are the least expensive among the reviewed technologies. Finally, the review shows that the financial benefits of products from wastewater are very small in comparison to overall system costs.

The case-study about Ho Chi Minh City in chapter 8 took as research questions:
What are the critical issues and practiced approaches to solutions in water and wastewater management in Ho Chi Minh City?
What are strengths and weaknesses of the chosen approaches, and in what way should they be amended?
This case-study is an important element of this thesis as it has yielded a deepended understanding of the global drainage and sanitation problematic through field study and literature survey. The encountered circumstances were the main argument to elaborate the participatory SANCHIS method to support a more effective approach to drainage and sanitation development.

Ho Chi Minh City in the first decade of the 21st century is characterized by a fast population growth of about 3.5% and an economic growth of around 10% per year, driven by massive domestic and foreign investment and creation of jobs in industry and services. This development takes place under circumstances of a still grossly inadequate environmental infrastructure, so that the city faces severe problems of air pollution, solid-waste management, groundwater over-extraction, pollution of waterways, frequent flooding and lack of open and green spaces. These problems are most acutely felt in the many unplanned low-income neighborhoods of the city.

Since about 1995 the city government, supported by international donors, is developing and implementing large projects to overcome the most pressing drainage and sanitation problems. The aggregated planned investment in these projects up to 2020 was estimated in in 2008 at nearly 3 billion USD. The emphasis in these projects is on restoration of drainage canals, the replacement and extension of sewers and treatment of sewage in the central districts. These urban upgrading projects testify of the political will to improve housing, infrastructure and urban services. They are accompanied by efforts to improve the legal and institutional framework of urban management, by a budding awareness of the need to change or adjust purely hierarchical planning and implementation practices and by building of informational, educational and professional capacity.

Despite the huge efforts, many of the city's environmental sanitation problems are still not under control, such as groundwater over-extraction, flooding and untreated sewage discharges. The problems of infrastructure are in part a consequence of historic under-investment. However, their replication in new fast-growing residential areas in the city proves that the responsible district agencies are still inadequately equipped to manage the land, and to develop and implement adequate land-use plans. Drainage in many new residential zones for example is very difficult as the guidelines for heightening of land prior to building are not, or insufficiently, enforced.

The case-study shows that problems of urban water management are rooted in: (1) fast growth of population and housing in the city, (2) very high land prices in the few planned zones of the city and the resulting lack of affordable housing to the majority of house seekers, (3) the unplanned nature of a large part of the new housing due to ineffective land management and planning arrangements, and (4) a lack of social building by the state. These problems are interrelated, and obviously drainage and sanitation problems can not be solved in isolation. Recent new plans for large-scale dyke construction along the main rivers of Ho Chi Minh City will reduce the flooding risks caused by high water levels in the rivers, but do not dispel the need of adequate land heightening in residential areas to support gravity transport of sewage and stormwater runoff (ICEM, 2009b; ICEM, 2009a).

A critical issue encountered in the on-going projects is the demolition of houses along canals resulting in the need of massive relocation of its inhabitants to new apartment blocks. The serious disadvantages of this practice, such as loss of income to those relocated and reemergence of slum areas in other parts of the city, point at the need of other approaches as well.

Much has been learned about alternative options of urban upgrading with active participation of low-income households in the Tan Hoa – Lo Gom project (1998-2006)(Verschure et al., 2006; Anh et al., 2007). It has resulted in several new developments in housing for the poor and pollution abatement that would not have been possible through the much less participatory approach applied in other projects. The analysis of this project recognizes two of the four transformations characteristic for increased participation and sustainability: a mixed technical infrastructure and multi-actor planning. Further research will be necessary to ascertain the impacts of this project's lessons on the on-going and future urban environmental upgrading projects.

One could say that in Ho Chi Minh City strong global and local market forces drive a modernization process beset with serious accompanying problems. Regulation and management of these forces and the consequences of their actions require determined action by the government and the society at large. However, many governmental agencies in Ho Chi Minh City seem overwhelmed by the accumulation of their tasks. As they struggle with a lack of professional capacity, unclear divisions of tasks and a lack of vision on urban development, many problems remain unsolved or even are exacerbated. Apparently, they could benefit much from new forms of collaboration within and among the state agencies and with non-state partners.

Chapter 9 reports the results of a study about the performance of 15 small public-commercial secondary wastewater-treatment plants with design capacities from 5 to 1,500 m^3/d taking as point of departure the research question: *How small-scale wastewater-treatment systems function and what lessons can be learned about sustainable wastewater treatment in Ho Chi Minh City?*

The 15 installations were a sample out of an unknown, but definitely much larger, number of small-scale plants belonging to hospitals, hotels, markets, high-rise buildings and residential projects. The study revealed the deficient functioning of most of the plants. None of the plants could be given the assessment of good performance. Only two showed a sufficient performance, meaning that these plants had a good design and operational status, though they did not fully comply with effluent requirements at the time of the study. The causes of failure in the remaining thirteen plants were analyzed as being connected to all stages of the plants' life cycle: technology choice, design, construction and operation.

The study is completed with recommendations for improvement. In the field of technology choice and design the most important recommendations are detailed analysis of sewage collection systems prior to the design of wastewater-treatment plants, provisions for monitoring flows, process water and sludge, improved durability of equipment and construction. With regard to operation and maintenance it is recommended to ensure the employment of expert personnel. Furthermore, the overall practice should be improved by new governmental regulations, research and enforcement. In particular, national guidelines for plant design are needed, which should include among other things an analysis of the generation of excess sludge in the various types of treatment technologies, so that sludge handling facilities be adapted to the requirements of the plants.

As small wastewater-treatment plants in Vietnam turned out to be prone to neglect and relatively expensive, this thesis recommends to limit their application to situations where treatment is crucial, such as hospitals and hotels that discharge to bathing waters, and that can not be treated in a more centralized way. It would be interesting to investigate what the Vietnamese practice could learn from the European practice in which small wastewater treatment plants are widely applied without many faults.

Chapter 10 presents the results of an application of the SANCHIS data-base developed in the chapters 4 until 7 to the situation in Ho Chi Minh City with as leading research question: *What are the most appropriate drainage and sanitation systems for Ho Chi Minh City?*

On the basis of the analysis of the drainage and sanitation infrastructure in Ho Ch Minh City three main different housing conditions were distinguished for which the most appropriate systems were selected. The three conditions are: new residential areas, unplanned upgrading areas and high-rise buildings. Feasible drainage and sanitation systems were identified for these three housing types using the screening aids elaborated in chapter 6. The chosen systems make use of regular flush toilets and urine-diverting flush toilets. In both systems transport of sewage and stormwater runoff occurs by separate sewers. Wastewater can be treated either by small-scale local plants or by larger-scale communal plants. Stormwater runoff is discharged to surface water without treatment. The use of urine-diverting toilets implicates collection and storage of urine and cartage to the site of further treatment and agricultural reuse. In a detailed comparison of two of the selected systems the consumption of water, the consumption and generation of energy and the emissions and recovery of organic matter, nitrogen and phosphorus were calculated using material flow analysis. The urine-diverting system has notable advantages of lower water and energy consumption, lower emissions and higher recovery of nitrogen and phosphorous. However, with respect to several other criteria the predicted performance is lower, due to higher requirements to institutional cooperation and end-user awareness, and lower convenience and cultural acceptability. With respect to costs of the two systems in Vietnam no conclusions could be drawn as only indicative European data were available. Comparison of the mass balances of the two systems shows that direct agricultural reuse of effluent from sewage-treatment plants is more effective than urine-diversion at source (without reuse of effluent) in benefiting from nitrogen and phosphorus in domestic wastewater. In Vietnam the direct reuse of treated effluent in agriculture would require large-scale storage, since there is no demand for irrigation water in the rainy season. Storage and transport would significantly add to the costs and reduce the relative advantage of effluent reuse over urine reuse.

In chapter 11 the two main lines of this thesis meet: the challenge of finding appropriate drainage and sanitation solutions in concrete intervention zones and a participatory approach to planning. The research questions at the basis of this chapter were:
What are the outcomes of the participatory SANCHIS method applied to drainage and sanitation problems in Ho Chi Minh City?
How could the SANCHIS method be improved based on the experiences of the workshops?
What are the strengths, limitations and perspectives of SANCHIS?
The answers to these questions were sought during two workshops in Ho Chi Minh City held in 2007.
The first workshop was held in an academic setting. It showed the suitability of the approach and allowed adjustments to the planning of future workshops and the support information. The participants were in particular enthusiastic about their fast learning about a large number of system options.
The second workshop was organized in the framework of the ISSUE-2 programme, which aims at improvement of sanitation infrastructure in Ho Chi Minh City and in Long An province. The emphasis in this workshop was on problem analysis, objective setting, screening and preliminary assessment, in particular of the attainment of site-specific objectives.
Stakeholders in Ho Chi Minh City chose for unplanned densely populated zones pour-flush toilets with settled combined and settled separate sewer systems. For the squatter zones in district 6 of the city where houses do not permit individual toilets communal toilet blocks with pour-flush toilets were selected. The application of separate sewer systems would be new in Ho Chi Minh City. Where sufficient land could be found the wastewater collected with a separate system could be treated in a local secondary treatment plant. Sewage pumps would have to be applied in areas with insufficient gradient for gravity transport. The workshop participants proposed various on-site systems for peri-urban zones with a rural character in Cu Chi district showing a preference for the integrated treatment and reuse of human and pig

dung. They explicitly rejected urine-diverting dry (Ecosan) toilets as they appeared to have a strong preference for flush toilets.

As the outcomes of the SANCHIS *process*, namely communal toilets in district 6 realized on the basis of the ISSUE-2 workshop, have not been evaluated at the moment of finalizing this thesis, the judgment was limited to the SANCHIS *method*, that is the multi-criteria decision analysis involving stakeholders. The method carried out in workshops led to a shared and deepened view of the addressed problem and its solutions, and it strengthened the commitment among stakeholders to realize the new infrastructure. The participation of stakeholders from a wide range of practices is likely leading to more specific options to choose from than if only provider-related experts had been offering options. It was concluded, that participatory multi-criteria decision methods are an essential element in a multi-stakeholder approach in infrastructure development and that they are promising tools in the transformation of infrastructure to increased suitability to local conditions, environmental sustainability and empowerment of actors that were not involved in the planning process before. Though the method by itself is no full guarantee to cost-effective and sustainable interventions, it certainly helped to clarify conflicts of interests and preferences, and pave the way for acceptance of solutions among users and providers. SANCHIS processes are in particular recommendable where the choice of a drainage and sanitation system is not obvious, conditions are inhomogeneous and stakeholders are searching for a common ground for action.

It was concluded after this workshop that a SANCHIS process requires more expert input about the technical performance of the selected drainage and sanitation systems than given during the first two workshops. Possibly an additional in-depth study, between a first and a second workshop session, would be required. At the proposed follow-up workshop experts and non- experts should reunite for a joint assessment based on transparent data, and for the trade-off of strengths and weaknesses of the compared options. In accordance with these experiences a two-stage procedure as shown in figure 12.1 was recommended (see section 11.5).

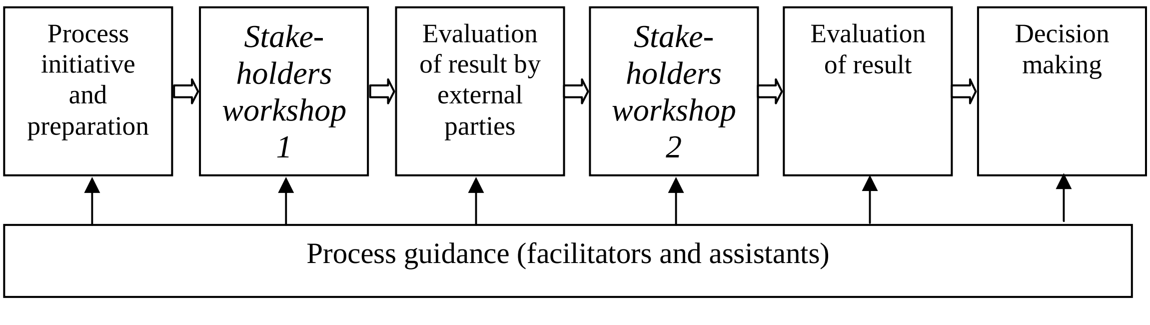


Figure 12.1 Recommended structure of the SANCHIS process

12.3 Vision on the use of SANCHIS in developing countries

In this thesis the improvement of drainage and sanitation infrastructure is being conceived as an endeavor in which social, environmental and technical issues are closely interrelated. The failing service provision to the poor, associated with government-dominated top-down approaches, and insufficient environmental sustainability, are sought to be overcome by a transition to new approaches in which non-state actors play an increasingly more important role in initiating, planning, implementing and managing drainage and sanitation infrastructure. This thesis assumes the emergence of hybrid forms of infrastructure governance with partnerships between government, private actors and grass-root organizations. The meant transition is the topic of several publications which have inspired and were elaborated parallel to the research of this thesis (McGranahan et al., 2001; Hasan, 2002; Tayler et al., 2003; EAWAG, 2005; Oosterveer and Spaargaren, 2010). If a wider array of stakeholders cooperates in shaping drainage and sanitation services, the need for mechanisms to support participatory planning and decision making emerges. The SANCHIS method and the participatory process in which this method is applied can be seen as a structured way to include social considerations in decision making about technical systems. The promises of SANCHIS, embedded in a process of stakeholder cooperation, are not only higher efficiency and legitimacy of the resulting infrastructure, but also empowerment of the involved actors. This empowerment could for example mean that communities and their leaders in developing cities learn from the drainage and sanitation implementation process how to approach other issues, such as the development of income-generating activities or other types of infrastructure improvement. It could also mean that engineers in state agencies obtain know-how about a wider range of technical options than they were used to work with, and become better informed about the concerns of low-income communities.

One could say that besides the Brown (improved access to sanitation for the poor) and Green (increased environmental sustainability) Agendas, introduced in chapter 2, also implicitly a Blue Agenda is being implemented. The key issue of the Blue Agenda is empowerment of the poor so that they can participate in and strengthen democratic procedures. It is argued here that SANCHIS is a method that could sustain such procedures, though much more is needed than just apply this method to attain empowerment of involved actor groups.

As shown in this thesis the first experiences with SANCHIS in Ho Chi Minh City have been very positive in terms of bringing stakeholders together, shaping innovative options and exchange of knowledge between engineers and representatives from communities. The chosen drainage and sanitation system options seemed to be well compatible with local conditions and the wishes of stakeholders. At the moment of finalizing this thesis the building of the selected infrastructure is not completed and an evaluation still has to demonstrate to what extent the SANCHIS process has contributed to the efficiency, sustainability and legitimacy of the implemented infrastructure, to breaking of path dependency in technology choice and empowerment of stakeholders. Such an evaluation of the outcome of SANCHIS processes could contribute to filling the theoretical gap identified in literature between the promises and the verified results of deliberative democratic procedures to which SANCHIS arguably belongs (Van Gunsteren, 2006; Bäckstrand et al., 2010).

12.4 Research agenda

The work on and with the SANCHIS method in Vietnam has revealed research needs in the domains of (1) environmental technology, (2) reuse-oriented drainage and sanitation infrastructure, (3) the application of SANCHIS, and (4) environmental governance.

(1) In the domain of on-site treatment, transport, treatment and reuse of municipal wastewater there is a need for applied technological research which would seek to make internationally known and promising technologies and technology chains applicable in Vietnamese (South-

East Asian) circumstances. Technologies would have to be tested at pilot and demonstration scale and not only in laboratories. The results should be widely disseminated. In order to share costs and benefits, it should preferably be undertaken in the framework of international partnerships. Promising wastewater-treatment technologies are UASB septic tanks, anaerobic upflow filters, mobile-bed bioreactors and downflow hanging sponges towers and constructed wetlands. In addition applied research on excess sludge generation, nitrogen and phosphate recovery and membrane technologies is recommended. The latter could play a useful role in making treatment plants more compact and efficient and are now finding an ever wider application. Therefore, also their strengths and limitations in developing countries deserve investigation. The proposed research should not only be focused on the technical, hygienic and environmental performance of technologies, but also on management requirements, user acceptance and costs. A focus point concerning compact wastewater treatment plants should also be mass production in order the reduce costs and increase reliability (Wilderer, 2001; Yang et al., 2001).

The material flow analysis applied in chapter 10 was based on international data about the source streams. A clear need was felt for more information about the quantities and qualities of the various domestic source streams and combined waste streams in Vietnam. Use of local data could lead to more accurate estimations of technology and system performance and consequently to better system design. The proposed collection of data about source streams would also have to pay attention to micro-pollutants with potentially harmful effects at reuse.

(2) Furthermore, research is recommended on drainage and sanitation infrastructure that aim at recovery of water, energy and nutrients, in particular on rainwater harvesting, and the reuse of effluents and sludges in agriculture. As much is known about the principles of the required technologies in the international scientific community, the emphasis in Vietnam would have to be laid on application, stakeholder collaboration, and management and acceptance issues in concrete projects.

(3) With respect to SANCHIS, several research paths could be taken. As indicated above a first task would be to evaluate efficiency, acceptance and sustainability of infrastructure realized through SANCHIS processes, possibly in comparison to the outcomes of a more conventional top-down approach to drainage and sanitation improvement. A second direction would be to further improve and extend SANCHIS, either for application of technology and system appraisal by local technology students and experts, or for stakeholder dialogues. In this thesis both roads have been explored but not followed until completion. It would be necessary to include tertiary treatment methods in the technology comparison.

(4) Finally, research on governance of drainage and sanitation provision is proposed. Environmental policy research in Vietnam up to now has been focused on industry and little has been done so far in the field of sanitation and municipal wastewater management (Dieu, 2003; Frijns, 2003; Khoa, 2006; Nhat, 2007). Nevertheless, this is an highly interesting research area. Huge investments take place in urban environmental upgrading accompanied by the emergence of new social relations and institutional arrangements. Comparison between Vietnam and countries in the region with significantly different governance systems like China, Thailand, and The Philippines could lead to elucidating insights. In the prescriptive parts of this research new feasible ways forward could be explored regarding integrated sustainable management of water resources.

12.5 Overall conclusions

The diagnosis of water and wastewater management practices in Ho Chi Minh City during the last 10 years, in particular in unplanned residential areas, showed among many other issues serious problems of flooding and a backlog in sanitation provision. Despite political will among the city's leadership and several ongoing city-wide upgrading projects, it appeared impossible to meet the demand for new infrastructure as urbanization outpaced the implementation efforts. In new fast-growing and low-lying residential areas of the city the wastewater disposal problems, addressed in economically more important areas, were replicated as the local government turned out incapable of adequate land and housing management. In particular the guidelines for land heightening prior to building were insufficiently enforced, so that in many new neighborhoods gravity drainage was difficult to realize while pumped drainage was too expensive and complicated to be considered.

An analysis of the performance of wastewater-treatment plants of hospitals, hotels and markets showed that only two out of fifteen plants functioned sufficiently. The most important recommendations are the introduction of national guidelines for design and ensuring the provision of regular and skilled operation and maintenance. Where possible a more centralized treatment should be aimed at, since it is expected to lead to higher efficacy at lower costs.

As the encountered problems appeared to be rooted in insufficiently equipped governmental agencies and inadequate institutional arrangements, the need of increased stakeholder participation and more emphasis on environmental sustainability in drainage and sanitation infrastructure planning and implementation was postulated. These transformations were in line with innovative strategies proposed in the international development community.
The proposed new approach required a method for selection and comparison of technologies in a participatory multi-stakeholder setting. Accordingly, the multi-criteria decision aid SANCHIS (Sanitation Choice Involving Stakeholders) was developed. This method has a wider scope than existing decision aids in that it includes innovative resource-recovery systems and treats sanitation and stormwater drainage in an integrated way. The latter is of special relevance to countries with a humid climate like Vietnam. More than other decision aids SANCHIS has an urban focus. SANCHIS enables the application of material flow analysis of water, organic matter, nitrogen and phosphorus to ascertain the repartition of these substances over the gaseous, liquid and solid end products of drainage and sanitation systems. Other important contributions of SANCHIS are a quantitative approach to methane emissions, energy consumption and capacity-cost relationships for wastewater transport and treatment technologies.

Application of SANCHIS to three different housing conditions in Ho Chi Minh City showed the preference for settled separate sewer systems with short transport lines for stormwater runoff. A comparison of systems with dual-flush toilets and urine-diverting flush toilets for housing in new planned residential areas pointed out the advantages with respect to the environment and the uncertainties regarding acceptance of the latter system option.
SANCHIS was also tested during workshops in Ho Chi Minh City. It was concluded that the SANCHIS method led to a shared and deepened view of the addressed problem and its solutions and a strengthened commitment among stakeholders to realize the new

infrastructure. The participation of stakeholders from a wide range of practices has likely delivered more specific options to choose from than if only provider-related experts had been offering options. The experiences confirmed the expectation that multi-criteria decision methods are an essential element in a participatory approach in infrastructure development and that they can be tools in the transformation of infrastructure to environmental sustainability and increased involvement of a variety of public, community and private formal and informal actors. Though the method by itself is no guarantee to cost-effective and sustainable interventions, it certainly helped to clarify conflicts of interests and strengthen acceptance of solutions.
SANCHIS processes seem in particular recommendable where the choice of new drainage and sanitation systems is not obvious and a common ground for action has to be found. Such conditions frequently occur in developing countries.

Finally, proposed further research concerns innovative environmental technologies, especially for wastewater treatment, reuse-oriented drainage and sanitation infrastructure and environmental governance related to urban drainage and sanitation in Vietnam, while in addition further elaboration and more applications of SANCHIS in developing countries in general are recommended.

SAMENVATTING

Inleiding

Een belangrijk deel van de bevolking in ontwikkelingslanden, in het bijzonder de armen in de slums en andere ongeplande stedelijke gebieden, heeft geen toegang tot adequate drainage en sanitatievoorzieningen met ernstige gevolgen voor gezondheid en welzijn. Deze dissertatie analyseert allereerst de oorzaken van dat gebrek aan voorzieningen en gaat vervolgens op zoek naar meer effectieve mechanismen voor een inclusieve en duurzame drainage en sanitatie implementatie in ontwikkelingslanden. Dit gebeurt op twee niveau's. Ten eerste het niveau van ontwikkelingssteden in het algemeen (hoofdstuk 2 tot 7), en ten tweede het niveau van Ho Chi Minh City in Vietnam (hoofstukken 8 tot 11). De case-study over Ho Chi Minh City is bedoeld als bron van verdiept inzicht en als plaats waar nieuwe benaderingen kunnen worden ontwikkeld en getest in een concreet drainage en sanitatieprogramma voor ongeplande en achtergestelde gebieden. Aangezien volgens de analyse het vermelde gebrek aan voorzieningen geworteld is in een *top-down* aanpak met een te beperkte betrokkenheid van de gebruikers van systemen, wordt een meer doelmatige benadering gezocht in een grotere bijdrage van gemeenschappen aan projectplanning, uitvoering en beheer zonder evenwel de belangrijke rol van overheidsdiensten te ontkennen. De belangrijkste bijdrage van deze dissertatie aan grotere betrokkenheid van belanghebbenden is SANCHIS (Sanitation Choice Involving Stakeholders), een methode voor participatieve technologiekeuze op het gebied van drainage en sanitatie. Dit hoofdstuk 12 vat stap voor stap de antwoorden op de in hoofdstuk 1 gestelde onderzoeksvragen samen.

Overzicht van de inhoud

Hoofdstuk 2 onderzoekt de de vraag: *welke zijn de belangrijkste uitdagingen en oplossingsrichtingen op het gebied van stedelijk waterbeheer in Het Zuiden?*
Stedelijke waterbeheer, in het bijzonder drainage van hemelwater en sanitatie kunnen beschouwd worden als een publiek goed, waarmee het voor de hand ligt dat betreffende regelgeving en beheer overheidstaken zijn. Zonder het zicht te verliezen op de historische successen van het beheer door de overheid in de ontwikkelde landen van het Noorden, wordt de *top-down* benadering van infrastructuurvoorziening onvoldoende in staat geacht de massa's armen in ontwikkelingslanden te bereiken. In de literatuur zijn nieuwe implementatie arrangementen voorgesteld, waarin marktpartijen en aan belangengemeenschappen gekoppelde netwerken de rol van overheidsdiensten aanvullen of zelfs vervangen, teneinde de doorbraak te bereiken die wordt nagestreefd met de Millennium Doelstellingen van de Verenigde Naties (McGranahan et al., 2001; EAWAG, 2005; WSP, 2009). Gebrek aan voorzieningen voor de armen is niet de enige tekortkoming van de momenteel gehanteerde aanpak. In verscheidene landen worden nieuwe technische systemen geïntroduceerd om infrastructuur op het gebied van stedelijk waterbeheer te verbeteren wat betreft emissiereductie en besparing en terugwinning van water, nutriënten en energie. Andere landen zullen naar verwachting deze aanpak volgen. Aansluitend op de hoopvolle verwachtingen omtrent een aanpak met grotere inbreng van direct betrokkenen en de zoektocht naar milieukundige duurzaamheid, postuleert hoofdstuk 2 de ondersteunende principes en de transformaties voor een verbeterde drainage- en sanitatiepraktijk. Deze transformaties zijn: (1)

een sterkere betrokkenheid van gebruikers, gemeenschapsorganisaties en de private sector in planning, besluitvorming, implementatie van infrastructuur, (2) een meer gedecentraliseerde organisatie van het beheer van infrastructuur, (3) besparen van hulpbronnen en reductie van emissies door het sluiten van kringlopen, en (4) de acceptatie van on-site en gedecentaliseerde drainage en sanitatie technologieën als legitieme alternatieven.
De positieve kijk op een versterkte rol van gemeenschappen in de implementatie van infrastructuur in deze dissertatie is gebaseerd op de verwachte gunstige effecten van een grotere betrokkenheid: namelijk versterking van het leren en het reflecteren, grotere transparantie bij de planning en besluitvorming, grotere betrokkenheid, en opbouw van capaciteit met een *spill-o*ver effect naar andere gemeenschapsactiviteiten.
De voorgestelde transformaties betekenen nieuwe institutionele arrangementen, met inbegrip van methoden om het participatieve selectieproces van drainage- en sanitatiesystemen te ondersteunen. De ontwikkeling van zo een methode, genaamd SANCHIS, wordt beschreven in de hoofdstukken 3 tot en met 7. Een essentiële vraag die bij een participatieve aanpak van planning en besluitvorming gesteld moet worden is of deze aanpak leidt tot meer effectieve en legitieme besluiten dan wanneer overheidsdiensten zouden handelen zonder of met veel minder inbreng van belanghebbende actoren. Het proces en de uitkomsten van een participatieve aanpak in Ho Chi Minh City worden besproken en beoordeeld in hoofdstuk 11.

Bij de ontwikkeling van de SANCHIS methode in hoofdstuk 3 was de centrale onderzoeksvraag: *wat zou een geschikte methode zijn voor planning en selectie van aangepaste en duurzame drainage- en sanitatiesystemen?*
Allereerst wordt technologieselectie gedefinieerd als deel van een gefaseerd planning proces: de interventiecyclus. Op grond van literatuur over multicriteriaanalyse wordt deze cyclus onderverdeeld in vijf stappen: probleemanalyse, definitie van doelen en criteria, zoeken naar systeemopties, uitwerken van de prestaties van deze opties en afwegen van sterkten en zwakten van de opties (Hammond et al., 1999). Deze stappen worden besproken en een nieuwe methodologie wordt voorgesteld voor toepassing bij de selectie van drainage- en sanitatiesystemen. Belangrijke kenmerken zijn technologiespecifieke en plaatsspecifieke meting van prestaties, en *screening* en vergelijking van opties. Voor het afwegen is de SMARTS procedure (Edwards and Barron, 1994) uitgekozen vanwege haar gebruiksvriendelijkheid en het gemak om resultaten te visualiseren (Olson, 1995). De voorgestelde multicriteriamethode wordt gekoppeld aan een methode van participatieve besluitvorming, omdat van zulk een proces belangrijke voordelen op het gebied van gezamenlijke probleemverheldering, snel leren, het ontstaan van draagvlak en betere interventies mogen worden verwacht. Tenslotte worden andere vergelijkbare methoden voor het ondersteunen van beslissingen geëvalueerd, namelijk SANEX, het Philippine Sanitation Sourcebook, de NETSSAF flowstream benadering en het EAWAG Compendium van sanitatiesystemen en technologieën (Loetscher, 1999; PHSSDA, 2007; Zurbruegg and Tilley, 2007; Tilley et al., 2008). In vergelijking met deze methoden legt SANCHIS meer nadruk op stedelijke drainage en sanitatie en minder op rurale oplossingen en meer op afvoer van regenwater en op innovatieve hergebruikgeörienteerde oplossingen.

De selectie van het optimale drainage en sanitatiesysteem uit een groep van mogelijke opties met behulp van multicriteriaanalyse vereist criteria waarmee systemen kunnen worden beoordeeld en vergeleken. Hierom is de leidende onderzoeksvraag bij hoofdstuk 4: *Welke zijn geschikte criteria voor de beoordeling van de aangepastheid en duurzaamheid van drainage* *en sanitatiesystemen?* Deze criteria werden geselecteerd op basis van literatuur en ervaring van de auteur. Bij de selectie is veel zorg besteed aan het voorkomen van overlap van de criteria en de formulering van geschikte indicatoren voor de meting van de mate waarin systemen aan de criteria voldoen. Het resultaat zijn een lijst van 2 plaatsspecifieke criteria voor *screening* en twee lijsten van respectievelijk 23 technologiespecifieke en enige relevante plaatsspecifieke criteria voor vergelijking van systeemopties. De technologiespecifieke criteria zijn gegroepeerd onder de hoofddoelstellingen technologische functionaliteit, bescherming van de gezondheid, bescherming van het milieu en grondstoffenvoorraden, sociale beheersbaarheid en economische wenselijkheid. Terwijl de prestaties van drainage en sanitatiesystemen wat de technologiespecifieke criteria betreft onafhankelijk zijn van de plaats van implementatie, worden de prestaties voor de plaatsspecifieke criteria geheel bepaald door de omstandigheden waarin een systeem wordt toegepast. Daarom kunnen de prestaties ten aanzien van technologiespecifieke criteria gemeten worden met objectieve indicatoren, terwijl de prestaties ten aanzien van plaatsspecifieke indicatoren worden vastgesteld in een dialoog van lokale deskundigen en andere belanghebbenden. In hoofdstuk 10 is een voorbeeld uitgewerkt een objectieve meting van systeemprestaties met behulp van de technologiespecifieke criteria. Beide typen criteria zijn gebruikt in bijeenkomsten van belanghebbenden in Ho Chi Minh City bij de selectie van drainage- en sanitatiesystemen voor verschillende districten in die stad (hoofdstuk 11).

Het hart van de SANCHIS methode is de selectie van haalbare drainage- en sanitatiesysteemopties voor een zekere interventiezone. Teneinde deze selectie te ondersteunen in de context van participatieve besluitvorming, of beroepsonderwijs, is in hoofdstuk 5 een lijst systeemopties ontwikkeld onder de onderzoeksvraag:
welke zijn de technologische systeemopties betreffende drainage en sanitatie die toepasbaar zijn in steden in ontwikkelingslanden?
Deze systeemopties zijn gedefinieerd als een samenstel van technologieën voor 5 verschillende functies: toiletten, *on-site* opslag en behandeling, transport, *off-site* behandeling en hergebruik/lozing. Daar de systeemopties op een eenvoudige manier gevisualiseerd moeten kunnen worden is een schetsmethode ontwikkeld met tekens die de verschillende technologieën (bouwstenen) symboliseren. De optielijst in hoofdstuk 5 bestaat uit 58 drainage en sanitatiesystemen, oftewel materiële ketens, onderverdeeld in 12 groepen van *on-site*, gemeenschapsgerichte *off-site* en centrale *off-site* systemen. De systeemopties bevatten 6 verschillende toilettypen: 2 typen droge toiletten, 2 typen spoeltoiletten en 2 toilettypen die afvalwaterstromen scheiden aan de bron. Terwijl de classificatie in hoofdstuk 5 de systeemopties groepeert naar de mogelijkheden om bronstromen in te zamelen, heeft de auteur ook nagedacht over een indeling gebaseerd op omgekeerde ketens (Grendelman and Huibers, 2010). De omgekeerde ketenbenadering stelt het hergebruik van eindproducten van drainage- en sanitatieketens, zoals irrigatiewater of compost, centraal en ordent systemen daarom naar de verschillende hergebruiksmogelijkheden (Mara et al., 2007). De kracht van deze benadering is dat zij alle aandacht en creativiteit richt op het sluiten van kringlopen. Aangezien deze benadering echter geen geschikt ordeningsprincipe voor alle systemen opleverde en veel minder bruikbaar leek voor systeemkeuze in het kader van SANCHIS processen in Vietnam, is zij verlaten.

De beoordeling van drainage en sanitatiesystemen geschiedt op basis van de prestaties van de bouwstenen die het systeem vormen (toiletten, on-site behandeling etc.) en aggregatie van deze prestaties tot een totale systeemwaardering. De prestaties van drainage- en sanitatietechnieken zijn uitgewerkt in een database in de hoofdstukken 6 en 7 gebruikmakend van de volgende onderzoeksvragen:

Welke zijn de technische, gezondheidskundige en milieukundige prestaties en welke factoren beperken de toepassingsmogelijkheden van de technologieën die tezamen de drainage- en sanitatiesystemen vormen beschreven in hoofdstuk 5?

Welke zijn de investerings- en operationele kosten van de technologieën die tezamen de drainage- en sanitatiesystemen vormen beschreven in hoofdstuk 5?

De beoordeling van technieken voor een concreet interventiegebied omvat twee stappen: (1) de *screening* om te onderscheiden tussen toepasbare en niet toepasbare technieken en (2) de vergelijking van de toepasbare technieken. Niet-toepasbaarheid, welke aangeeft dat het gebruik van een zekere techniek in de onderzoekssituatie moet worden afgeraden, wordt bepaald met behulp van restrictieve factoren. Op basis van restrictieve factoren zijn in hoofdstuk 6 *screening* matrices ontwikkeld voor de 12 drainage- en sanitatiesysteemgroepen uit hoofdstuk 5 en voor rioolwaterzuiveringstechnieken. Voor de vergelijking van systeemopties worden zowel de plaatsspecifieke als de technologiespecifieke criteria uit hoofdstuk 4 gebruikt. De hoofdstukken 6 en 7 presenteren een uniek overzicht van een grote hoeveelheid informatie die de beoordelaar in staat stelt de prestaties van drainage- en sanitatietechnieken en systemen te vergelijken zonder diep in andere literatuur te hoeven duiken. Het literatuuronderzoek voor hoofdstuk 6 heeft verscheidene veelbelovende nieuwe afvalwaterbehandelingstechnieken voor ontwikkelingslanden aan het licht gebracht, zoals de UASB septic tank, de *baffled anaerobic septic tank*, de helofytenfilters voor ruw rioolwater, de bewegend-bed bioreactoren en neerwaarts doorstroomde torens met hangende sponzen. Hoofdstuk 7 integreert data over kosten van de bouwstenen van drainage en sanitatiesystemen tot een schatting van de kosten van totale systemen. Het hoofdstuk besluit met de volgende volgorde van de goedkoopste tot de duurste systeemopties: individuele *on-site* systemen met droge toiletten < individuele *on-site* systemen met spoeltoiletten < centrale off-site systemen met reguliere spoeltoiletten, urinescheidende toiletten en droge toiletten < conventionele en op hergebruik gerichte *off-site* systemen met twee tot vier gescheiden stromen toegepast op de schaal van een kleine gemeenschap.

Systeemopties met urinescheidende toiletten voor de terugwinning van nutriënten blijken slechts weinig duurder dan systeemopties met reguliere toiletten. De vergelijking van primaire plus secundaire afvalwaterbehandelingstechnieken voor tropische gebieden met een gering ruimtegebruik laat zien dat UASB reactoren, UASB reactoren met facultatieve vijvers en UASB reactoren met oxidatiebedden de minst dure zijn van de onderzochte technieken. Tenslotte toont het overzicht aan, dat de opbrengsten van producten uit afvalwater in financiële termen vooralsnog zeer gering zijn in vergelijking met de totale systeemkosten.

De case-study over Ho Chi Minh City in hoofdstuk 8 gaat uit van de onderzoeksvragen:

Welke zijn de belangrijkste problemen en wijzen van aanpak in het water- en afvalwaterbeheer in Ho Chi Minh City?

Welke zijn de sterkten en zwakten van de gekozen benaderingen en hoe zouden zij aangepast moeten worden?

Deze case-study is een belangrijk onderdeel van de dissertatie, omdat zij via veldstudie en literatuuronderzoek veel inzicht heeft opgeleverd in de globale drainage- en sanitatie-problematiek. De omstandigheden in de stad vormden de aanleiding om een participatieve technologieselectiemethode (SANCHIS) uit te werken als onderdeel van een meer effectieve aanpak van de drainage- en sanitatieontwikkeling. Ho Chi Minh City heeft in het eerste tiental jaren van de 21e eeuw te maken gehad met een snelle bevolkingsgroei van 3.5% en een economische groei van omstreeks 10% per jaar. Deze werden gedreven door forse nationale en internationale investeringen en groei van werkgelegenheid in industrie en diensten. Deze ontwikkeling heeft plaats onder omstandigheden waarin de milieukundige infrastructuur zeer ernstig tekortschiet, zodat de stad kampt met enorme problemen op het gebied van de luchtverontreiniging, vervuiling van de waterwegen, frequente overstromingen en een gebrek aan open en groene ruimte. Deze problemen worden het sterkst gevoeld in de vele ongeplande arme wijken van de stad.

Sinds ongeveer 1995 heeft het stadsbestuur, ondersteund door internationale donoren, grote projecten ontwikkeld en uitgevoerd teneinde de meest urgente drainage- en sanitatieproblemen te overwinnen. De gezamenlijke investeringen in deze projecten tot het jaar 2020 bedragen volgens schatting in 2008 bijna 3 miljard USD. De nadruk in deze projecten ligt op het herstel van de afvoerkanalen, de vervanging en uitbreiding van riolen en de behandeling van rioolwater in de centrale districten. Deze stedelijke saneringsprojecten getuigen van de politieke wil om huisvesting, infrastructuur en stedelijke diensten te verbeteren. Zij gaan samen met pogingen om de wettelijke en institutionele kaders van het stedelijk beheer te verbeteren, met een ontluikend bewustzijn van de noodzaak tot aanpassing van de zuiver hiërarchische planning- en implementatiepraktijk en het versterken van capaciteit op het gebied van informatie, onderwijs en professionele kwaliteit.

Ondanks de omvangrijke inspanningen zijn vele van de problemen van de stad nog niet onder controle, zoals de overmatige onttrekking van grondwater, overstromingen in bebouwde gebieden en lozing van ongezuiverd afvalwater. De problemen met de infrastructuur zijn ten dele het gevolg van gebrek aan investeringen in het verleden. Hun herhaling in nieuwe snelgroeiende woongebieden in de stad bewijst echter, dat de verantwoordelijke districtsdiensten nog steeds onvoldoende toegerust zijn om grond te beheren en adequate bestemmingsplannen te ontwikkelen en uit te voeren. De afvoer van overtollig water blijft in vele woongebieden zeer lastig doordat de richtlijnen voor het ophogen van land voorafgaand aan bebouwing niet of onvoldoende in praktijk worden gebracht.

De *case-study* toont aan, dat de problemen van het stedelijk waterbeheer geworteld zijn in (1) snelle groei van de bevolking en woningen (2) zeer hoge grondprijzen in de enkele geplande gebieden van de stad en het daarmee gepaard gaande gebrek aan betaalbare huisvesting voor de meerderheid van de woningzoekenden, (3) het ongeplande karakter van een groot deel van de nieuwe woningen tengevolge van ontoereikende grondbeheer- en planningsystemen en (4) een gebrek aan sociale woningbouw door de overheid. Deze problemen houden verband met elkaar en het is duidelijk dat drainage- en sanitatieproblemen niet in isolatie opgelost kunnen worden. Uitvoering van recente plannen voor grootschalige dijkaanleg langs de grote rivieren in Ho Chi Minh City zal het overstromingsrisico veroorzaakt door hoge rivierwaterniveau's weliswaar verminderen, maar de noodzaak van maaiveldverhoging in woongebieden voor vrijvervaltransport afvalwater en regenwater niet wegnemen.(ICEM, 2009b; ICEM, 2009a).

Een punt van zorg in de huidige projecten is de afbraak van huizen in *slums* langs de kanalen gepaard gaande aan massale hervestiging van inwoners in speciale appartementenblokken. De ernstige nadelen van deze praktijk, zoals verlies van inkomen na hervestiging en het ontstaan van nieuwe slums elders in de stad wijzen op de noodzaak van een andere aanpak.

Er is veel geleerd over alternatieve mogelijkheden tot stadssanering met actieve participatie van huishoudens in het Tan Hoa - Lo Gom project (1998-2006)(Verschure et al., 2006; Anh et al., 2007). Het heeft geresulteerd in verscheidene nieuwe ontwikkelingen in de woningbouw

voor groepen met lagere inkomens en in het tegengaan van vervuiling die niet mogelijk waren geweest met de veel minder participatieve aanpak van andere projecten.
De analyse van dit project onderkent twee van de vier voor participatie en duurzaamheid kenmerkende transformaties uit hoofdstuk 2: een gemengde technische infrastructuur en planning door meerdere actoren. Verder onderzoek is nodig om de impact van het project op huidige en toekomstige infrastructurele projecten op de langere termijn vast te stellen.
Men zou kunnen zeggen, dat in Ho Chi Minh City sterke mondiale en locale marktkrachten een modernisatieproces stuwen welk leidt tot ernstige bijkomende problemen. Controle en sturing van deze krachten en hun gevolgen vragen om vastberaden actie door de overheid en de maatschappij als geheel. Veel overheidsdiensten echter lijken overweldigd door de opeenhoping van taken. Terwijl zij worstelen met een gebrek aan professionele capaciteit, onduidelijke taakverdelingen en een gebrek aan visie op stedelijke ontwikkeling, blijven vele problemen onopgelost of worden zelfs erger. Zij zouden veel baat kunnen hebben bij nieuwe vormen van samenwerking.

Hoofdstuk 9 rapporteert een studie naar de prestaties van 15 kleine publiek-commerciële secundaire afvalwaterzuiveringsinstallaties met ontwerpcapaciteiten tussen de 5 en 1,500 m^3/d met als uitgangspunt de onderzoeksvraag: *hoe functioneren kleine afvalwater-zuiveringsinstallaties in Ho Chi Minh City en wat kan er geleerd worden over duurzame afvalwaterbehandeling*?
De 15 installaties waren een selectie uit een onbekend, maar zeker veel groter, aantal kleine installaties behorende bij ziekenhuizen, hotels, markten en hoogbouwprojecten en woning-bouwprojecten. Geen van de onderzochte installaties kreeg het predikaat ‘goed’. Van slechts twee werd het functioneren voldoende geacht, hetgeen betekent, dat deze installaties voor de meeste doch niet voor alle parameters voldeden de effluenteisen op het moment van het onderzoek maar wel goed ontworpen waren en goed beheerd werden. De oorzaken van gebreken bij de overige 13 installaties bleken verbonden te zijn met alle stadia van de levenscyclus: technologiekeuze, ontwerp, constructie en exploitatie. De studie concludeert tot 17 aanbevelingen voor verbetering. Op het gebied van de technologiekeuze en het ontwerp zijn de belangrijkste aanbevelingen een gedetailleerde en geïntegreerde analyse van reeds aanwezige inzamelings- en zuiveringssystemen, (simpele) voorzieningen voor de meting aan debieten, proceswater en slib, en verbeterde duurzaamheid van toegepaste apparatuur en constructie. Met betrekking tot exploitatie en onderhoud is in het bijzonder het aanstellen van deskundig personeel belangrijk. De praktijk als geheel moet verbeterd worden met nieuwe regelgeving door de overheid, onderzoek en controle op naleving van regels. In het bijzonder zijn nationale richtlijnen voor ontwerp van installaties nodig. Daar kleine installaties gevoelig zijn voor verwaarlozing en naar verhouding duur bleken, beveelt deze dissertatie aan de toepassing te beperken tot situaties waar de afvalwaterbehandeling cruciaal is, zoals ziekenhuizen en hotels die lozen nabij badstranden en waar een meer centrale aanpak van de zuivering niet mogelijk is. Het zou interessant zijn na te gaan wat de Vietnamese praktijk kan leren van Europa waar kleine installaties veelvuldig worden toegepast zonder veel storingen.

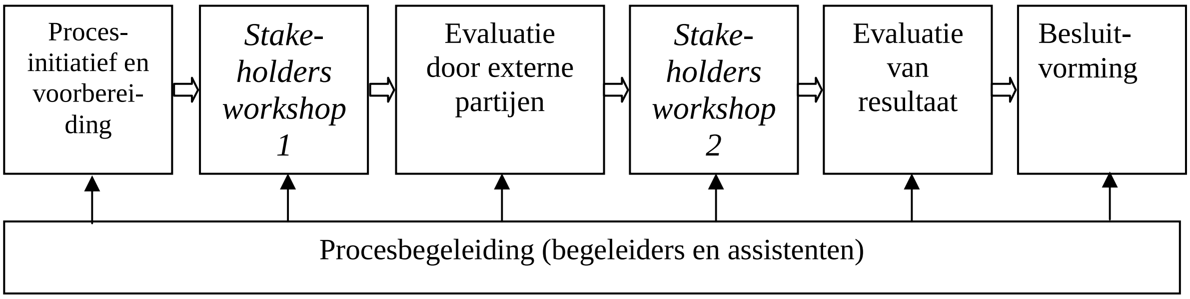
Hoofdstuk 10 presenteert de resultaten van een toepassing van de SANCHIS *data-base* ontwikkeld in de hoofdstukken 4 tot en met 7 met als leidende onderzoeksvraag: *wat zijn de meest geschikte drainage- en sanitatiesystemen voor Ho Chi Minh City?*
Op basis van de analyse van de drainage- en sanitatieinfrastructuur in Ho Chi Minh City in hoofdstuk 8 worden voor drie typen woningbouw de meest geschikte systemen geselecteerd.

De drie typen zijn: nieuwe planmatig gebouwde woongebieden, ongeplande woongebieden en hoogbouw. De drainage- en sanitatiesystemen voor deze drie woningbouwtypen werden geselecteerd met behulp van de *screening*hulpmiddelen van hoofdstuk 6. De geselecteerde systemen maken gebruik van reguliere spoeltoiletten of urinescheidende toiletten. Deze beide systemen maken gebruik van gescheiden transport van huishoudelijk afvalwater en hemelwater. Het afvalwater kan behandeld worden ofwel met kleinschalige locale ofwel met grootschaliger centrale installaties. Het hemelwater gaat onbehandeld naar het oppervlaktewater. Het gebruik van urinescheidende toiletten impliceert verzameling en opslag van urine en transport per as naar de plaats van verdere behandeling en landbouwkundig hergebruik. Voor een gedetailleerde vergelijking van een regulier en een urinescheidend systeem voor nieuwe planmatig gebouwde woonwijken werden de consumptie van water, de consumptie en opwekking van energie, en de emissies en terugwinning van organische stof, stikstof en fosfor berekend met behulp van een analyse van massastromen. Het urinescheidende systeem heeft aanzienlijke voordelen op het gebied van water- en energieverbruik, lagere emissies en een hogere mate van terugwinning van stikstof en fosfor. Wat betreft enkele andere criteria is de voorspelde prestatie lager dan van het reguliere systeem, tengevolge van hogere eisen die een urinescheidend systeem stelt op het gebied van institutionele samenwerking en bewustzijn van eindgebruikers, en een lagere waardering wat betreft gebruiksgemak en culturele acceptabiliteit. Met betrekking tot de kosten van de twee systemen in Vietnam konden geen definitieve conclusies getrokken worden aangezien voor de vergelijking alleen Europese gegevens ter beschikking stonden welke in de sterk verschillende omstandigheden in Ho Chi Minh City van zeer beperkte waarde zijn. Vergelijking van de massabalansen van de twee systemen laat zien, dat direct landbouwkundig hergebruik van effluent van rioolwaterzuiveringsinstallaties effectiever is dan urinescheiding aan de bron (zonder hergebruik van het effluent) bij het benutten van het stikstof en de fosfaat in huishoudelijk afvalwater. In Vietnam zou het direct hergebruik van effluent in de landbouw echter grootschalige opslag vereisen, aangezien er geen vraag naar irrigatiewater is in het regenseizoen. Deze opslag en het transport zouden de kosten van hergebruik verhogen en het relatieve voordeel van het effluenthergebruik ten opzichte van urinehergebruik verminderen.

In hoofdstuk 11 komen de twee hoofdlijnen van de dissertatie bij elkaar: de vraag naar geschikte drainage- en sanitatieoplossingen in concrete interventiegebieden en die van een participatieve aanpak van planning. Deze vragen werden beantwoord gedurende twee workshops in Ho Chi Minh City in 2007. De daarbij gebruikte onderzoeksvragen waren:
Welke zijn de uitkomsten van de participatieve SANCHIS methode toegepast op drainage- en sanitatieproblemen in Ho Chi Minh City?
Hoe zou SANCHIS verbeterd kunnen worden op basis van de ervaringen van de workshops?
Welke zijn de sterkten, beperkingen en vooruitzichten van SANCHIS?

De eerste workshop die in een academische omgeving werd gehouden toonde de bruikbaarheid van de aanpak en het hulpmateriaal aan. De deelnemers waren vooral enthousiast over de snelle manier waarop inzicht in een grote hoeveelheid systeemopties verkregen werd.
De tweede workshop werd georganiseerd in het kader van het ISSUE-2 programma dat zich richt op verbetering van sanitatievoorzieningen in Ho Chi Minh City en in de provincie Long An. De nadruk in deze workshop lag op probleemanalyse, het formuleren van doelstellingen,

screening en een voorlopige beoordeling van opties in het bijzonder op het bereiken van plaatsspecifieke doelen.
De deelnemers kozen *pour-flush* toiletten met gecombineerde en gescheiden rioolstelsels voorzien van voorbezinking met septic tanks voor de ongeplande dichtbevolkte gebieden. Voor de *squatter* gebieden in district 6 in Ho Chi Minh City waar de woningen te klein zijn voor inbouw van spoeltoiletten werden communale toiletblokken met *pour-flush* toiletten geselecteerd. De toepassing van gescheiden rioolsystemen is nieuw in Ho Chi Minh City. Indien er plaatselijk voldoende land beschikbaar is, zou het ingezamelde afvalwater in locale secundaire zuiveringsinstallaties behandeld kunnen worden. Rioolwaterpompen zouden toegepast moeten worden in gebieden met een onvoldoende gradiënt voor vrijvervaltransport. Diverse *on-site* systemen werden voorgesteld voor peri-urbane zones met een meer ruraal karakter in Cu Chi district met een voorkeur voor een geïntegreerd systeem voor de behandeling van menselijke en dierlijke mest. De deelnemers aan een van de workshops verwierpen expliciet de urinescheidende droge toiletten, daar zij een uitgesproken voorkeur bleken te hebben voor spoeltoiletten.
Aangezien de eindresultaten van het SANCHIS proces, namelijk de communale toiletten in district 6 welke gebouwd zijn op advies van de workshop, nog niet geëvalueerd zijn op het moment dat deze dissertatie afgerond werd, is de beoordeling beperkt tot de SANCHIS methode, d.w.z. de participatieve multi-criteriaanalyse. De methode uitgevoerd in de *workshops* leidde tot een gedeeld en verdiept inzicht in problemen en oplossingen in het studiegebied en het versterkte het sociale draagvlak voor de nieuwe infrastructuur. De deelname van belanghebbenden met diverse achtergronden leidt waarschijnlijk tot meer specifieke opties dan wanneer alleen de opties van deskundigen verbonden aan overheidsdiensten in beschouwing waren genomen. Er werd geconcludeerd, dat multicriteria-analysemethoden een essentieel element zijn in een aanpak waarin velen belang hebben bij de gemaakte keuzes. Ook zijn zij een veelbelovend hulpmiddel in de transformatie van infrastructuur naar groter doelmatigheid, milieukundige duurzaamheid en emancipatie van degenen die bij het proces betrokken zijn.
Hoewel de methode zelf geen volledige garantie biedt voor kosteneffectieve en duurzame interventies, hielp zij zeker belangen- en voorkeursconflicten aan het licht te brengen en de weg te effenen voor acceptatie van oplossingen door gebruikers en overheidsdiensten. SANCHIS processen zijn in het bijzonder aan te bevelen in situaties waarin de keuzen niet voor de hand liggen, de condities inhomogeen zijn en belanghebben zoeken naar een gemeenschappelijk basis voor actie.
Het werd duidelijk, dat het uitnodigen van en de informatieverschaffing over SANCHIS aan de deelnemers zeer belangrijke zaken in het SANCHIS proces zijn. Een conclusie was dan ook, dat veel aandacht besteed moet worden aan de uitnodiging van diegenen die directe belangen hebben bij de verbetering van drainage en sanitatie in het studiegebied en deskundigen die *feedback* kunnen geven op de voorgestelde oplossingen.
Er werd eveneens geconcludeerd, dat een SANCHIS proces deskundige beoordeling vereist met betrekking tot technische prestaties van geselecteerde drainage en sanitatiesystemen. Een aanvullende nadere studie tussen een eerste en een tweede workshop sessie kan nodig zijn. In de voorgestelde tweede workshop zouden deskundigen en niet-deskundigen opnieuw bijeen kunnen komen voor de afweging van sterkte en zwakten van de vergeleken opties op basis van heldere gegevens. Op basis van deze ervaringen werd een SANCHIS procedure met twee *workshops* voorgesteld als weergegeven in figuur 12.1.



Figuur 12.1 Aanbevolen structuur van het SANCHIS proces.

Visie op het gebruik van SANCHIS in ontwikkelingslanden

In deze dissertatie wordt de verbetering van de drainage- en sanitatieinfrastructuur opgevat als een onderneming waarin sociale, milieukundige en technische vraagstukken nauw verweven zijn. Er wordt gepoogd de falende dienstverlening aan de armen welke samenhangt met een door een overbelaste overheid gedomineerde hiërarchische benadering en gebrekkige milieukundige duurzaamheid te overwinnen door een transitie naar nieuwe benaderingen waarin niet-overheidsactoren een belangrijker rol spelen in het initiëren, plannen, uitvoeren en beheren van infrastructuur.
Deze dissertatie gaat ervan uit dat hybride vormen van bestuur ten aan zien van infrastructuur zullen ontstaan met samenwerkingsverbanden van overheid, private actoren en basisorganisaties. De bedoelde transitie is het thema van verscheidene publicaties die zowel deze dissertatie inspireerden als tegelijkertijd ontwikkeld werden.
Waar een bredere groep belanghebbenden deelneemt aan het vormgeven van drainage en sanitatiediensten ontstaat de behoefte aan mechanismen om participatieve planning en besluitvorming in goede banen te leiden. De SANCHIS methode en het participatieve proces waarin zij wordt toegepast kan gezien worden als een gestructureerde manier om sociale afwegingen te betrekken in de besluitvorming over technische systemen. De beloften van SANCHIS ingebed in een samenwerking van belanghebbenden zijn niet alleen een grotere efficiëntie en legitimiteit van de resulterende infrastructuur, maar ook *empowerment* van de betrokken actoren. Deze versterking van hun positie zou bijvoorbeeld kunnen betekenen dat gemeenschappen en hun leiders in ontwikkelingssteden via het drainage en sanitatieproces leren om ook andere vraagstukken aan te pakken, zoals de ontwikkeling van inkomensgenererende activiteiten of andere vormen van infrastructuurverbetering. Het zou ook kunnen betekenen, dat ingenieurs van overheidsdiensten kennis verwerven over méér technische opties dan waar zij gewoonlijk mee werkten en dat zij beter geïnformeerd raken over de problemen in arme gemeenschappen.
Men zou kunnen zeggen, dat naast de Bruine en Groene Agenda's impliciet een Blauwe Agenda wordt uitgevoerd. Het belangrijkste punt in de Blauwe Agenda is de versterking van de positie van de armen zodat zij deel kunnen nemen aan en bij kunnen dragen aan democratische procedures. Hier wordt gesteld dat SANCHIS een methode is die zulke procedures kan ondersteunen, hoewel er veel meer nodig is dan alleen het toepassen van deze methode om positieversterking van de betrokken actoren te bereiken.
Zoals aangetoond in de dissertatie zijn de eerste ervaringen met SANCHIS zeer positief in termen van het samenbrengen van belanghebbenden, nieuwe oplossingen genereren en de uitwisseling van kennis tussen technici en vertegenwoordigers van gemeenschappen.

De gekozen drainage- en sanitatieoplossingen leken goed aan te sluiten bij de locale omstandigheden en de wensen van de belanghebbenden. Op het moment dat deze dissertatie werd afgerond was de constructie van de geselecteerde infrastructuur nog niet voltooid en moet een nadere evaluatie aantonen in welke mate het SANCHIS proces heeft bijgedragen aan doelmatigheid, duurzaamheid en draagvlak van de infrastructuur, aan het doorbreken van pad- afhankelijkheid bij de techniekkeuze en bekrachtiging van de positie van de stakeholders. Zo een evaluatie van SANCHIS processen zou kunnen bijdragen aan het vullen van de theoretische leemte die in de literatuur wordt gesignaleerd tussen de beloften en de geverifieerde resultaten van deliberatieve democratische procedures, waartoe de SANCHIS methode gerekend mag worden (Van Gunsteren, 2006; Bäckstrand et al., 2010).

Onderzoeksagenda

Het werk aan en met de SANCHIS methode in Vietnam heeft onderzoeksvragen aan het licht gebracht op het gebied van (1) milieutechnologie, (2) hergebruikgerichte drainage- en sanitatieinfrastructuur, (3) de toepassing van SANCHIS, en (4) het bestuur op het gebied van milieuzaken. (1) Op het gebied van *on-site* behandeling, transport, behandeling en hergebruik van stedelijk afvalwater is er een behoefte aan toegepast technologisch onderzoek, dat er op gericht is internationaal bekende en veelbelovende technieken en techniekketens toepasbaar en doelmatig te maken voor Vietnamese (Zuidoost Aziatische) omstandigheden.Technieken zouden getest moeten worden op *pilot*- and demonstratieschaal en niet alleen in laboratoria, en de resultaten zouden breed verspreid moeten worden. Teneinde de kosten en baten te delen, zou dit onderzoek bij voorkeur dienen plaats te vinden in het kader van internationale samenwerkingsverbanden. Veelbelovende afvalwaterbehandelingstechnieken in dit verband zijn UASB-septic tanks, anaërobe upflowfilters, bewegend-bed bioreactoren, beplante filters en neerwaarts doorstroomde torens van hangende sponzen. Ook wordt toegepast onderzoek aan de slibaanwas, stikstof en fosfaatterugwinning en aan membraantechnieken voorgesteld. De laatste zouden van belang kunnen zijn om zuiveringsinstallaties meer compact en efficiënt te maken. Zij worden in toenemende mate met succes toegepast en ook in ontwikkelingslanden verdienen haar voordelen en beperkingen nader onderzoek. Het voorgestelde onderzoek dient niet alleen aandacht te besteden aan technische, hygiënische en milieuprestaties maar ook aan vereisten op het gebeid van beheer, een acceptatie door gebruikers en aan kosten. Een punt van aandacht bij compacte afvalwaterzuiveringsinstallaties moet ook zijn de mogelijkheid van massaproductie teneinde kosten te reduceren en de betrouwbaarheid te vergroten.
De analyse van materiaalstromen welke werd toegepast in hoofdstuk 10 was gebaseerd op internationale gegevens over de bronstromen. Er bleek een ernstige behoefte aan meer kennis over de hoeveelheden en eigenschappen van de verschillende huishoudelijke afvalwaterstromen in Vietnam. Het gebruik van locale gegevens zou kunnen leiden tot meer nauwkeurige schattingen van techniek- en systeemprestaties en dientengevolge tot een beter systeemontwerp. De voorgestelde verzameling van locale gegevens over bronstromen zou ook aandacht moeten besteden aan microverontreinigingen met potentieel negatieve effecten bij hergebruik.
(2) Voorts wordt onderzoek aanbevolen op het gebied van drainage- en sanitatieinfrastructuur dat zich richt op de terugwinning van water, energie en nutriënten, in het bijzonder op de benutting van regenwater en het hergebruik van effluenten en slib in de landbouw. Daar er in de internationale wetenschappelijke wereld veel bekend is over de principes van de vereiste

technieken, zou de nadruk moeten liggen op toepassing, betrokkenheid van maatschappelijke actoren en vragen rond beheer en acceptatie in concrete projecten.
(3) Met betrekking tot SANCHIS zouden verscheidene onderzoekswegen ingeslagen kunnen worden. Zoals boven aangegeven zou een eerste taak zijn de doelmatigheid, duurzaamheid en acceptatie van via SANCHIS processen gerealiseerde infrastructuur te evalueren, zo mogelijk in vergelijking met infrastructuur die via een meer conventionele *top-down* benadering tot stand is gekomen. Een tweede richting zou kunnen zijn SANCHIS verder te ontwikkelen, ofwel voor toepassing van techniek- en systeembeoordeling door locale studenten en deskundigen, ofwel in dialogen van belanghebbenden in situaties van concrete interventies.
In deze dissertatie zijn beiden wegen verkend, maar er is zeker een vervolg mogelijk. Het zou nodig kunnen zijn ook tertiaire zuiveringsmethoden te betrekken bij de techniekvergelijking.
(4) Tenslotte wordt onderzoek aan bestuurlijke aspecten rond drainage en sanitatie aanbevolen. Onderzoek op het gebied van milieubeleid in Vietnam is tot op heden sterk gericht geweest op de industrie en weinig is nog gedaan op het gebied van sanitatie en stedelijk afvalwaterbeheer. Niettemin is stedelijke infrastructuur een uiterst interessant onderzoeksterrein. Er wordt immers zeer veel geïnvesteerd in deze sector, waarbij nieuwe sociale relaties en institutionele arrangementen ontstaan. Een vergelijking tusen Vietnam en landen in de regio met significant verschillende bestuurssystemen, zolas China, Thailand en de Filippijnen zou tot verhelderende inzichten kunnen leiden. In de prescriptieve gedeelten van dit onderzoek zouden nieuwe en begaanbare wegen op het gebied van duurzaam beheer van water geëxploreerd kunnen worden.

Eindconclusies

De diagnose van water- en afvalwaterbeheer in Ho Chi Minh City gedurende de laatste 10 jaar, in het bijzonder in de ongeplande woongebieden, wijst onder meer op ernstige problemen op het gebied van overstromingen en de achterstand op het gebied van sanitatie. Ondanks de politieke wil bij het stadsbestuur en verscheidene omvangrijke saneringsprojecten is het onmogelijk gebleken aan de vraag naar nieuwe infrastructuur te voldoen. In nieuwe snelgroeiende en laaggelegen woongebieden van de stad worden de afvalwaterproblemen die wel aangepakt worden in de economisch belangrijker gebieden gerepliceerd, omdat het verantwoordelijk locaal bestuur niet in staat blijkt tot een toereikend beheer van grond en woningbouw. In het bijzonder worden de richtlijnen voor het ophogen van land voorafgaand aan bebouwing niet uitgevoerd, zodat in vele nieuwe woonwijken vrijvervalriolering moeilijk is te realiseren, terwijl drukriolering vanwege hoge kosten en technische ingewikkeldheid niet in beschouwing genomen kan worden.
Een analyse van de prestaties van installaties voor de afvalwaterbehandeling van ziekenhuizen, hotels en markten toont aan, dat slechts aan twee van de vijftien installaties het predikaat voldoende gegeven kon worden. De belangrijkste aanbevelingen zijn de introductie van nationale richtlijnen voor ontwerp en het garanderen van regelmatig en deskundig beheer en onderhoud. Waar mogelijk dient behandeling meer gecentraliseerd te worden, daar verwacht mag worden dat dit doelmatiger en goedkoper is.
Aangezien de aangetroffen problemen geworteld lijken in onvoldoend toegeruste overheidsinstanties en ontoereikende institutionele arrangementen, werd de behoefte aan grotere participatie van belanghebbenden en meer nadruk op milieukundige duurzaamheid in planning en implementatie van drainage en sanitatie gepostuleerd. Deze transformaties sloten aan bij innovatieve strategieën voorgesteld in de internationale ontwikkelingsgemeenschap.

De grotere betrokkenheid van belanghebbenden vereist een methode voor de selectie en vergelijking van technieken in een participatieve omgeving. In aansluiting hierop werd de SANCHIS methode ontwikkeld. Deze methode heeft een breder aandachtsgebied dan bestaande hulpmethoden bij de besluitvorming aangezien zij nieuwe systemen voor terugwinning van grondstoffen omvat en verwerking van afvalwater en hemelwater op een geïntegreerde wijze behandelt. Dit laatste is van speciale betekenis in landen met een nat klimaat, zoals Vietnam. Meer ook dan andere methoden richt SANCHIS zich op steden. SANCHIS maakt het mogelijk de verdeling van water, organische stoffen en nutriënten over de gasvormige , vloeibare en vaste eindproducten van drainage en sanitatiesystemen vast te stellen. Andere belangrijke bijdragen van SANCHIS zijn een kwantitatieve benadering van methaanemissies, energieconsumptie en capaciteit-kosten relaties voor afvalwatertransport en -behandelingstechnieken.
Toepassing van SANCHIS op drie verschillende woningbouwsituaties in Ho Chi Minh City toonde de voorkeur aan voor gescheiden riolering met voorbehandeling in septic tanks en met korte transportleidingen voor hemelwater. Een vergelijking van systemen met dual-flush en urinescheidende spoeltoiletten voor woningen in nieuwe geplande gebieden liet zien, dat de laatste optie voordelen heeft op milieugebied, maar omgeven is door onzekerheden wat betreft acceptatie. SANCHIS werd ook getest gedurende workshops in Ho Chi Minh City. Er werd geconstateerd, dat de SANCHIS methode leidde tot een gedeeld en verdiept inzicht van het bestudeerde probleem en zijn oplossingen en een versterkte betrokkenheid onder de deelnemers bij de uitvoering van de nieuwe infrastructuur. De deelname van belanghebbenden met diverse achtergronden heeft waarschijnlijk meer keuzemogelijkheden opgeleverd dan indien uitsluitend deskundigen van de overheden opties zouden hebben voorgelegd. De ervaringen bevestigen de verwachting van de auteur, dat de multicriteriamethoden een essentieel element in een participatieve benadering van de infrastructuurontwikkeling zijn en dat zij nuttig gereedschap kunnen zijn bij de transformatie van infrastructuur naar milieukundige duurzaamheid en een toegenomen betrokkenheid van actoren uit de publieke, private en collectieve sector.
Hoewel de methode *per se* geen garantie is voor kosteneffectieve en duurzame interventies, helpt zij zeker belangenconflicten te verhelderen en de acceptatie van oplossingen te versterken. In ontwikkelingslanden is de keuze van systemen dikwijls niet bij voorbaat duidelijk en is het belangrijk een gezamenlijke basis voor actie te vinden. Dat zijn gunstige omstandigheden voor de toepassing van SANCHIS.
Voorgesteld onderzoek tenslotte betreft nieuwe milieutechnieken, in het bijzonder voor de afvalwaterbehandeling, hergebruikgerichte drainage en sanitatiesystemen, en bestuurlijke aspecten verbonden aan drainage en sanitatie in Vietnam, terwijl eveneens verdere uitwerking en meer toepassingen van SANCHIS in ontwikkelingslanden in het algemeen worden aanbevolen.

TÓM TẮT

Phần lớn dân số ở các nước đang phát triển đang đối mặt với sự thiếu thốn nghiêm trọng cơ sở hạ tầng về nước uống – nước cấp, hệ thống thoát nước và quản lý chất thải rắn. Điều này gây ảnh hưởng bất lợi đến sức khỏe cộng đồng, hạnh phúc, kinh tế và môi trường. Đồng thời, sự gia tăng tiêu thụ sẽ làm cạn kiệt nhanh chóng các nguồn tài nguyên thiết yếu và đe dọa đến điều kiện sống. Nhận thức về tính bền vững trong sản xuất và tiêu thụ đang hình thành đã trở thành một điều cần thiết không thể tránh khỏi.

Đầu tiên, trong chương 2 luận án này trình bày tổng quan các tài liệu liên quan đến những nguyên nhân và phương hướng cơ bản để giải quyết các vấn đề về thoát nước và vệ sinh ở các nước đang phát triển. Mặc dù, chính phủ các nước đã nỗ lực mở rộng và cải thiện cơ sở hạ tầng, nhưng dường như họ không thành công trong việc tìm ra giải pháp thỏa đáng để đáp ứng nhu cầu của người dân. Một trong những nguyên nhân của việc thiếu kinh phí triển khai rộng rãi dường như là do phương pháp tổ chức thực hiện các dự án cơ sở hạ tầng không được trang bị đầy đủ và các tổ chức nhà nước manh mún.

Do đó, theo những tài liệu đã xuất bản trên thế giới, tăng cường sự tham gia của các tổ chức liên quan và bộ phận tư nhân trong việc phát triển và quản lý cơ sở hạ tầng đã được thừa nhận là xu hướng tất yếu và cần thiết. Hơn thế nữa, bản thân những người sử dụng cơ sở hạ tầng, các đại diện cho người sử dụng ở cấp độ quận, các cụm dân cư và các chuyên gia trong những lĩnh vực khác nhau tham gia vào quá trình qui hoạch cùng với các nhà qui hoạch và các chuyên gia xây dựng dân dụng của các cơ quan nhà nước. Bằng cách này, những người dân bị thiệt thòi về quyền lợi sẽ có nhiều cơ hội để cải thiện những lợi ích của họ.

Thêm vào đó, việc thoát nước và vệ sinh trên thực tế yêu cầu một sự chuyển đổi trạng thái từ hệ thống sử dụng các nguồn tài nguyên giá trị và xả thải vào môi trường sang hệ thống bền vững về môi trường, góp phần vào quá trình khép kín chu trình vật chất. Khi chuỗi thoát nước và vệ sinh trở thành hợp phần ngày càng quan trọng trong những lĩnh vực hoạt động xã hội khác như cấp nước, công nghiệp, nông nghiệp, giải pháp đa ngành là cần thiết trong việc hướng dẫn quá trình chuyển đổi trạng thái này. Những phân tích trước đây đã đưa đến việc thừa nhận trong chương 2 về bốn hình thái chuyển đổi được tóm tắt như sau: từ qui hoạch tập trung và ra quyết định sang qui hoạch có sự tham gia của nhiều thành phần, từ quản lý tập trung sang quản lý bằng nhiều thành phần, từ cơ sở hạ tầng tập trung sang cơ sơ hạ tầng dạng hỗn hợp, và từ sự sử dụng tài nguyên không hạn chế sang tiêu thụ tiết kiệm và khép kín chu trình vật chất.

Khi số lượng các thành phần tham gia vào quá trình lập qui hoạch tăng lên và nhu cầu những giải pháp nằm ngoài việc xem xét dựa trên các giải pháp kỹ thuật thông thường, các phương pháp được yêu cầu để lựa chọn một cách hợp lý và được tổ hợp từ những phương án hệ thống khả thi khác nhau cho tình huống được nghiên cứu. Một phần quan trọng của luận án này bao gồm việc soạn thảo chi tiết phương pháp SANCHIS (Sanitation Choice Involving Stakeholders), một phương pháp tham vấn tổ hợp cho việc chọn lựa hệ thống thoát nước và vệ sinh trên cơ sở phân tích đa tiêu chí. Các nguyên tắc của phương pháp này được nêu chi tiết ở chương 3. Điểm cốt lõi của phương pháp SANCHIS là sàng lọc các giải pháp hệ thống khả thi

ra khỏi một lượng lớn các giải pháp tiềm năng bằng việc sử dụng một số các tiêu chí đặc thù về vị trí và sau đó lựa chọn các giải pháp hệ thống khả thi thích hợp nhất bằng cách sử dụng cả hai tiêu chí đặc thù về công nghệ và đặc thù về vị trí.

Trong chương 4, ba nhóm tiêu chí đặc thù về công nghệ, vị trí và chỉ số để đánh giá các giải pháp hệ thống được thiết lập trên cơ sở tham khảo các tài liệu quốc tế. Trong số các nhóm tiêu chí này, 5 tiêu chí được phân loại như sau: tiêu chí về công nghệ, sức khỏe, môi trường, xã hội và kinh tế.

Trong chương 5, danh sách 58 giải pháp hệ thống thoát nước và vệ sinh đã được thiết lập, phân loại thành 12 nhóm hệ thống. Các giải pháp hệ thống thoát nước và vệ sinh được mô tả trong nghiên cứu này như là các chuỗi công nghệ, bao gồm nhà vệ sinh, hầm tự hoại, xử lý nước thải đô thị và nước mưa chảy tràn. Tái sử dụng nước thải sau xử lý và thải bỏ các chất thải sau xử lý đã được xem xét như là các mối liên kết trong các chuỗi này. Để có thể đánh giá khả năng ứng dụng và hiệu quả của những hệ thống trong một tình huống nào đó, chương 6 và chương 7 mô tả các đặc điểm của nhà vệ sinh, xử lý tại chỗ, vận chuyển, xử lý nước thải bên ngoài và các công nghệ xử lý bùn thải tương ứng với các tiêu chí đã được mô tả ở chương 4. Chương 6 đặc biệt thảo luận về các điều kiện cần thiết của yếu tố kỹ thuật tốt và hiệu quả về môi trường của các công nghệ được sử dụng. Chương 7 xem xét chi phí của công nghệ và hệ thống. Nội dung từ chương 4 đến chương 7 cùng thể hiện cơ sở dữ liệu của SANCHIS. Việc phân tích vấn đề và phương án dự kiến cho việc lựa chọn hệ thống thoát nước và vệ sinh (như đã mô tả trong các chương từ chương 2 đến chương7) đã được kiểm chứng bằng các nghiên cứu điển hình ở thành phố Hồ Chí Minh – Việt Nam (trình bày trong những chương còn lại, từ chương 8 đến chương 11).

Nghiên cứu điển hình đã thực hiện một mặt để hiểu rõ các vấn đề trong quản lý nước đô thị và những cơ hội để thay đổi ở các nước đang phát triển, mặt khác đặt ra phạm vi thảo luận và kiểm chứng các ý tưởng mới. Trong phương án được chọn, sự cải thiện cơ sở hạ tầng thoát nước và vệ sinh được mô tả trong mối liên hệ với công tác phát triển nhà và sự phát triển không đồng đều ở những khu vực đã qui hoạch và chưa qui hoạch của thành phố.

Chương 8 trước hết mô tả những cơ quan tham gia công tác quản lý nước ở thành phố Hồ Chí Minh. Một cách tổng quát, bối cảnh thực hiện công tác quản lý nước trong những thập niên trước đây trùng hợp trong nhiều khía cạnh với những phân tích đã đề cập ở trên đối với các nước đang phát triển. Điều này thực sự đặc biệt ở những khu dân cư phát triển thiếu qui hoạch. Những khu vực này gặp phải các vấn đề nghiêm trọng và ùn tắc trong hạ tầng thoát nước và vệ sinh. Mặc dù nhân lực sẽ thuộc chính quyền địa phương và nhiều dự án cải tạo đang triển khai vẫn không thể đáp ứng được nhu cầu lớn của một thành phố đang phát triển. Những khu vực phát triển nhanh và cơ sở hạ tầng kém phát triển bị tái lập những vấn đề đang được giải quyết ở những khu vực trung tâm kinh tế quan trọng. Chính quyền địa phương tỏ ra thiếu năng lực để quản lý hợp lý đất đai, quản lý qui hoạch phát triển nhà và cơ sở hạ tầng. Đặc biệt, chính quyền không áp đặt các hướng dẫn nâng cấp cao trình đất trước khi xây dựng và hậu quả là các đường cống thoát nước tự chảy khó có thể thực hiện được, trong khi các đường cống thoát nước sử dụng bơm được nhìn nhận là rất phức tạp và đắt tiền đối với những khu vực này. Việc thiếu đo đạc kỹ lưỡng cho hạ tầng thoát nước và đường cống ở những khu vực này đã gia tăng nguy cơ ngập lụt, ô nhiễm nguồn nước mặt và đất.

Chương 8 cũng bao gồm nội dung đánh giá dự án Tân Hóa – Lò Gốm (1998 - 2006), là dự án tập trung vào mục đích cải thiện cơ sở hạ tầng thoát nước và phát triển nhà của thành phố. Dự án này được chọn cho nghiên cứu do phương pháp có tính thực nghiệm và rõ ràng. Hai trong số bốn hình thái chuyển đổi đã đề cập ở trên trong việc hiện đại hóa hạ tầng thoát nước và vệ sinh đã được thực hiện trong dự án này, cụ thể là có sự tham gia nhiều hơn mức bình thường các thành phần liên quan trong khâu qui hoạch, triển khai và thực hiện một hệ thống hạ tầng phức hợp.Không tìm thấy có sự chuyển đổi về sự tham gia mạnh mẽ hơn trong công tác quản lý hạ tầng và tái sử dụng các vật liệu có giá trị từ các nguồn thải. Nhân tố quan trọng trong dự án Tân Hóa - Lò Gốm là những thực nghiệm nâng cấp các hộ dân có thu nhập thấp hiện đang sống dọc con kênh bị ô nhiễm và dự án cung cấp các dịch vụ tại chỗ. Các thực nghiệm đã trình diễn phương án phá dỡ các ngôi nhà thông thường và tái định cư người dân đến những căn hộ tập trung ở những nơi khác trong thành phố. Điều đáng kể là những người dân sau khi tái định cư có thể tiếp tục sống và làm việc cùng với những người hàng xóm cũ của mình. Nghiên cứu điển hình về thành phố Hồ Chí Minh tổng hợp các phương án thực hiện liên quan đến cấp nước, thoát nước và vệ sinh, phát triển nhà và môi trường đô thị. Một chính sách được ủng hộ là sử dụng tối ưu các nguồn nước khác nhau trong thành phố. Chính sách này đã mang lại những cơ hội cải thiện điều kiện sống của người dân thành phố Hồ Chí Minh.

Do việc thực hiện toàn bộ các nhà máy xử lý nước thải qui mô lớn ở thành phố Hồ Chí Minh sẽ cần nhiều thời gian, chương 9 nghiên cứu vấn đề liệu các nhà máy xử lý nước thải qui mô nhỏ không tập trung có thể là một giải pháp bền vững trên mặt trận chống ô nhiễm nguồn nước mặt. Nghiên cứu đã khảo sát hiệu quả của các trạm xử lý đang có của các bệnh viện, khách sạn và khu thương mại trong và chung quanh thành phố Hồ Chí Minh. Kết quả thu được là một bức tranh ảm đạm. Chỉ có hai trong số mười lăm trạm xử lý đã khảo sát có thể đánh giá là có hiệu quả. Các khuyến cáo quan trọng nhất là cần có hướng dẫn của nhà nước đối với việc thiết kế, lắp đặt các trạm xử lý, tạo điều kiện cơ bản thích hợp cho công tác vận hành thường xuyên, chuyên nghiệp và bảo trì các trạm xử lý. Thêm vào đó cần nhắm tới phương án có nhiều hơn các nhà máy xử lý nước thải tập trung tùy theo khả năng của từng địa phương vì nó tạo ra điều kiện để đạt hiệu quả cao hơn, giảm chi phí xử lý cho một đơn vị thể tích nước thải. Điều đó không có nghĩa là giải pháp tập trung là giải pháp duy nhất để đạt kết quả mong muốn.

Cuối cùng, phương pháp SANCHIS, phương pháp qui hoạch bằng cách tham vấn tổ hợp đối với hệ thống thoát nước và vệ sinh được áp dụng theo hai cách trình bày trong chương 10 và 11. Trong chương 10, các hệ thống thoát nước và vệ sinh phù hợp được chọn cho 3 dạng phát triển nhà khác nhau ở thành phố Hồ Chí Minh, cụ thể là các khu dân cư mới qui hoạch, khu dân cư đang cải tạo chưa qui hoạch và những khu dân cư mới xây dựng. Phương pháp này cho phép lựa chọn và so sánh một cách đơn giản các hệ thống thoát nước trên cơ sở tiêu chí công nghệ và sử dụng các dữ liệu đã tổ hợp trong Chương 6 và 7. Ví dụ đối với những khu dân cư mới qui hoạch cho thấy rằng hệ thống thoát nước áp dụng kiểu nhà vệ sinh có thùng giật nước và tách riêng nước tiểu có nhiều ưu điểm về mặt môi trường so với các kiểu nhà vệ sinh giật nước thông thường, đặc biệt về khía cạnh tiêu thụ nước và năng lượng, phát thải và thu hồi nitơ, phôtpho. Tuy nhiên, việc tận dụng các thành phần có giá trị vẫn có thể thực hiện được bằng cách tái sử dụng nước thải từ các nhà vệ sinh thông thường sau khi đã xử lý hợp lý trong nông nghiệp. Trong Chương 11, phương pháp tham vấn đã được áp dụng tại hai hội thảo để lựa chọn hệ thống thoát nước ở các quận khác nhau trên địa bàn thành phố Hồ Chí Minh. Phương pháp sử dụng tại hội thảo cho phép chia sẽ và nhìn nhận kỹ hơn về các vấn đề cần giải quyết, các giải pháp có thể áp dụng và đạt được sự nhất trí giữa các tổ chức liên quan đối với phương án cơ sở hạ tầng mới. Sự tham gia của nhiều đối tượng liên quan với kinh nghiệm thực tế khác nhau cho phép đưa ra nhiều phương án đặc biệt để lựa chọn hơn là chỉ dựa trên một số phương án do một số chuyên gia cung cấp. Kinh nghiệm này giúp khẳng định rằng yêu cầu lý thuyết của phương pháp phân tích đa tiêu chí là yếu tố cần thiết theo hướng phương án kỹ thuật phát triển cơ sở hạ tầng dựa trên nhu cầu của địa phương. Đây là công cụ hữu hiệu giúp phát triển cơ sở hạ tầng theo hướng phát triển bền vững về môi trường và tăng cường sự tham gia của cộng đồng, các tổ chức nhà nước và tư nhân. Mặc dù bản thân SANCHIS không bảo đảm có thể can thiệp về mặt chi phí-hiệu quả và tính bền vững, nhưng có thể giúp xác định những mâu thuẫn giữa sự quan tâm và sở thích và mở đường cho sự chấp thuận các giải pháp giữa người sử dụng và nhà cung cấp. Quy trình SANCHIS được kiến nghị áp dụng đặc biệt ở những nơi mà việc lựa chọn hệ thống thoát nước không rõ ràng, điều kiện không đồng nhất và các tổ chức liên quan đang tìm kiếm giảp pháp chung để thực hiện. Tóm lại, có thể kết luận rằng cơ sở dữ liệu SANCHIS cung cấp cái nhìn khái quát mới về kỹ thuật, hệ thống và các đặc tính của chúng. Cơ sở dữ liệu cho phép các tổ chức liên quan trong quy trình ra quyết định cho một lĩnh vực nhất định nào đó xác định sự khác biệt giữa các giải pháp công nghệ và hệ thống thoát nước và vệ sinh hợp lý và không hợp lý và so sánh một cách chi tiết hiệu quả giữa các hệ thống đã lựa chọn.

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GLOSSARY

Appropriate (-ness, technology, system)
An appropriate sanitation technology or system provides a socially and environmentally acceptable level of service or quality of product with full health benefits and at least economic costs (Kalbermatten et al., 1982).

Black water
Black water is wastewater originating from toilets. Black water usually contains faeces, urine, toilet paper or other materials used for anal cleansing and the water used for flushing.

Brown water
Brown water is toilet wastewater which consists of flush water, toilet paper and faeces originating from urine-diverting flush toilets. It can be considered as black water minus urine. In practice brown water is not free from urine, since complete source separation of urine is unattainable.

Cartage
Transportation of sanitation-related wastes (faecal sludge, urine, faecal matter) from residential areas by means of manual transport, cart or tanker truck. An example is the cartage of *septage* obtained on emptying septic tanks.

Community On-Site Sanitation
Sanitation system laid out at the scale of a community or group of communities. The area covered by community on-site systems may vary. The maximum sewage flow from community on-site systems is arbitrarily set at 4,000 m^3 per day (20,000 inhabitants) with a maximum covered area of 100 ha (see: **Scale**).

Cost effectiveness
A cost effective policy meets an (environmental) objective at the lowest possible costs using the least amount of economic resources (Callen and Thomas, 1999). Cost-effectiveness analysis can be used in the comparison of projects when the costs are known, but the benefits in monetary terms are not (Munier, 2004, p 114).

Criterion
Test, principle, rule, canon or standard by which anything is judged or estimated
(The Compact Edition of the Oxford English Dictionary, 1972).
In this thesis the word criterion is used most to mean ‘a parameter used to evaluate the contribution of a technology to meet an objective’ (Munier, 2004, p 47). A criterion for technical functionality of a treatment technology is reliability. The degree of compliance with the criterion is measured by means of one or more **indicators**.

Decentralized Sanitation and Reuse (DESAR)
Decentralized sanitation and reuse is defined in opposition to centralized sanitation. Whereas centralized sanitation is considered to discharge most of the utilizable components of wastewater with the effluent into the environment, DESAR systems aim at recovery of these

components. Decentralization is considered as a means to enable cost-effective reuse of recovered products such as biogas, nutrients and water in the proximity of the place of generation. In addition to DESAR systems there are DESA systems, decentralized systems without deliberate recovery of utilizable products. Examples of these DESA systems are the sewage collection, treatment and disposal systems at residential areas, hotels, markets and hospitals in Vietnam. There is no absolute limit to the maximum nor the minimum number of users of a DESA(R) system. The maximum capacity of a decentralized municipal system has been arbitrarily set at 50,000 PE or an area of 250 ha. 50,000 PE is the approximate point on the cost-capacity curve for wastewater-treatment plants where the annual costs per capita start to strongly increase with decreasing capacity. In this thesis decentralized systems include clustered, community on-site and small-scale sewage collection, treatment and reuse systems. Typically reutilization of products from wastewater requires the prevention of pollution of the wastewater with toxic and persistent substances such as heavy metals.

Drainage and sanitation
The societal activities associated with collection, transport, treatment, disposal and reuse of municipal wastewater, including stormwater, domestic, public-commercial and industrial wastewater.

Energy
Energy consumption and production in drainage and sanitation systems are expressed in megajoules primary energy (MJpe) which refers to primary sources of energy such as fossil fuels or combustible biomass. By combined heat and power plants primary energy is converted to approximately 1/3 electrical energy (MJe) and 2/3 heat (MJth).

Environmental Sustainability
The environmental and resource impact of a societal subsystem is such, that it ‘meets the needs of the present , without compromising the ability of future generations to meet their own needs. (World Commission on Environment and Development, 1987). See also Sustainability.

Excreta
Excreta indicates urine and faeces. In practice excreta also includes anal cleansing material.

Faecal sludge
Faecal sludge is undigested or partially digested slurry resulting from the storage and treatment of sewage, black water, brown water and excreta. Specific forms of faecal sludge are sludge formed in septic tanks (**septage**) and digestate formed in anaerobic digesters that process human excreta. A typical feature of faecal sludge is the possible content of human pathogenic organisms.

Faecal matter
Solid material resulting from the dehydration of faeces in dry urine-diverting toilets.

Feeder system
The feeder system is that part of the sewer system that collects wastewater from houses, public-commercial objects, enterprises and streets. Typical features of the feeder system are rainwater inlets and house connections.
Footprint
Land requirement of a technology or system. A distinction is made between net and gross footprint. The net footprint is the net surface covered by components of the treatment technology or system. The gross footprint includes the net footprint plus land required for miscellaneous structures and zoning.

Functional element
A functional element is a part of **the (urban) water system** with a function in providing drinking and household water, consuming water, collecting, storing and treating wastewater, collecting, transporting and treating stormwater, and the environmental compartments soil and water with an ecological function.

Grey water
Domestic wastewater generated by the use of drinking water for personal hygiene, laundry , food preparation and other non-toilet uses.

Implementability
The probability that sanitation facilities can be constructed within the period and with the financial resources usually required for the selected type of system in favorable conditions (Loetscher, 1999, p 81).

Indicator
Parameter for quantitative or qualitative measurement of criterion fulfillment.

Individual on-site treatment of wastewater
Systems such as the septic tank that treat wastewater of individual houses at the place of its origin.

Integrated Sustainable Waste Management (ISWM)
Tool for analysis, planning and decision-making in urban waste management developed in the framework of the Urban Waste Expertise Programme by WASTE Consultants in The Netherlands between 1995 and 2001 (Van de Klundert and Anschuetz, 2001; UNEP, 2009).

Off-site treatment
Treatment of wastewater or wastes at a relatively long distance from the place where it is generated. Off –site treatment requires transport of pure (like urine, faeces and grey water) or mixed source streams (like mixed black water and grey water).

On-site treatment
Treatment of wastewater or wastes on or near the place where they are generated. A distinction is made between household on-site and community on-site treatment.

Opportunity Cost
Opportunity costs can be understood as the potential return on good alternative investment opportunities, or the return that was missed, due to the investment in the project under study (Thuesen and Fabrycky, 2001).

Scale of sewerage and wastewater treatment
5 capacity groups of sewerage and wastewater-treatment systems are distinguished. The following table lists the systems and the capacity ranges used in this study:

System class	Capacity (PE)
Individual on-site and cluster systems	5 – 50
Community systems	>50-2,500
Small-scale systems:	>2,500- 50,000
Medium-scale systems:	>50,000- 500,000
Large-scale systems	> 500,000

As per Crites and Tchobanoglous (1998) small scale and decentralized system have wastewater output smaller than 1 million gallon/d (3,785 m^3/d) which corresponds to about 30,000 P.E.

SANCHIS
The acronym SANCHIS refers to 'Sanitation choice involving stakeholders'. A distinction is made between the SANCHIS process, the SANCHIS method and the SANCHIS data base. A SANCHIS process designates a multi-stakeholder participatory planning and decision making process in drainage and sanitation infrastructure which makes use of the SANCHIS method. The SANCHIS method is a protocol for application of multi-criteria decision analysis (MCDA) in a multi-stakeholder context. The theoretical background of the method is sketched in chapter 3 of this thesis. The SANCHIS data-base is a tool for system and technology selection which is part of the method and can be used during the process. This data base has been detailed in chapters 4 until 7. The application of SANCHIS method and data-base is tested in chapters 10 and 11.

Sanitation
The means of collecting and disposing of excreta and community liquid wastes in a hygienic way so as not to endanger the health of individuals and the community as a whole (WHO, 1987) cited by Loetscher(1999, p 5). Otterpohl and co-authors (1997) add maintenance of soil fertility as an additional objective of sanitation. Sanitation requires sanitation systems, which are a chain of sanitation technologies: e.g. the combination of pour-flush toilet, septic tank, small-bore sewerage, off-site treatment, disposal of effluent to river and disposal of sludge to land.

Sanitation technology
A sanitation technology is a functional element of a sanitation system. In a sanitation systems two or more technologies are combined to enable the system to perform its role. A septic tank is an example of a sanitation technology.

Septage
Septage or septic-tank sludge is the mixture of sludge and wastewater that is collected at emptying septic tanks. Septage is a form of **faecal sludge**.

Sludge
Sludge is solid matter in water associated with wastewater collection and treatment operations. Sludge is present in sewage in the form or inorganic and organic solids. It is also generated during biological wastewater-treatment processes. This biological sludge mainly consists of living and dead microorganisms. Removal and treatment of sludge are important functions of wastewater-treatment plants that should enable its safe disposal.

Source stream
The notion of source stream is used to indicate forms of wastewater as they are generated at their source, e.g. urine, faeces, black water, grey water, stormwater, etc.

Structural and non-structural measures
Structural measures in the field of drainage and sanitation improvement imply the hardware: appliances, toilets, pipe networks, treatment plants, etc. Non-structural measures are meant to influence the institutional set-up (orgware) and user behavior related to the hardware. This behavior can be altered by awareness raising and education (software).

Sustainability
Many meanings can be attributed to the notion of sustainability. Widely accepted is the one proposed by the World Commission on Environment and Development that defines sustainable development as development which meets the needs of the present population without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987; Munier, 2004). As a guiding principle in the realization of urban infrastructure, the principle includes: saving of resources through minimization materials and energy in production and consumption, a shift from resources of mineral origin to bio-based and renewable materials, resource recovery from waste streams and advanced reduction of harmful emissions to the environment. A second meaning refers to the probability that infrastructure once completed serves beneficiaries according to its design throughout its design life (Loetscher, 1999, p 81).

Technology and technology chain
The term *technology* is used in this thesis for an element or building block of a drainage and sanitation system that fulfills a certain function. Toilet, on-site storage and treatment, on-site reuse, on-site disposal, transport, off-site treatment, off-site reuse and off-site disposal are the functional elements. The system as a whole is considered as consisting of one or more chains of technologies.

Total Annual Costs per Household (TACH)
The TACH includes the capital costs and recurrent costs associated with drainage and sanitation systems. If the system yields products with a market value the recurrent financial benefits have to be subtracted from the recurrent costs. TACH is the parameter used in this thesis to compare the costs of different technologies and systems.

Unrestricted irrigation
In the practice of irrigation with effluent from municipal wastewater-treatment plants the risk of disease transmission is a key issue. This risk is to a high degree determined by the abundance of faecal pathogenic organisms in the irrigation water. As identification of pathogens is cumbersome, usually the abundance of thermotolerant organisms of the E. coli group (the so called faecal coliforms) is measured to quantify the risk of infections. If the water contains less than 1000 faecal coliforms/100 ml, it can be used for the irrigation of the most critical type of crops, namely those that are normally eaten raw (WHO, 2006). This is named unrestricted irrigation. At higher faecal coliform abundances restrictions in the crop choice are recommended to reduce the risk of infections.

Urban water system
This term refers to one system or a combination of subsystems, with each their functional elements associated with the provision of water for various uses, including the ecological functions of surface and groundwater, the management of rainwater, the appliances for the use of water and the handling of excreta and wastewater in households, industry and public areas, and finally the collection, treatment, reuse and disposal of all categories of wastewater and associated solids. The urban water system may encompass several **technology chains**.

Unplanned area
An (urban) area is unplanned if site preparation and building has not followed a spatial and architectural (master) plan, either because such plan did not exist at the time of building, or because the local authorities did not enforce a plan. Usually unplanned building is carried out by squatters or individual land title holders.

Waste (water) streams
Wastewater or waste streams are source streams (see above) or combinations of source streams generated through human activities. In this thesis the term waste(water) streams in particular refers to streams that pass through drainage and sanitation systems.

Yellow water
A mixture of urine and toilet flushing water.

APPENDIX 1 EFFLUENT REQUIREMENTS IN VIETNAM

This appendix presents the following Vietnamese standards for effluent requirements:

Industrial wastewater	(TCVN 5945-1995, 1995)
Domestic wastewater	(TCVN 6772-2000, 2000)
Industrial wastewater	(TCVN 5945-2005, 2005)

Appendix 1.1 Effluent Requirements in Vietnam according to TCVN 5945 – 1995

VIETNAM STANDARD **TCVN 5945 – 1995**

INDUSTRIAL WASTEWATER STANDARD FOR DISCHARGE

1. Scope

1.1 This standard specifies the parameter limits and maximum allowable concentrations of substances in industrial wastewater discharges.
In the standard "industrial wastewater" means: water or wastewater generated by work or production processes taking place at industrial, servicing and trading premises, etc.

1.2 This standard is applied to control the quality of industrial wastewater before it is discharged into a water body.
"Water body" means: inland water, including any reservoir, pond, lake, river, stream, canal, drain, spring or well, any part of the sea near the shores, and any other body of natural or artificial surface or subsurface water.

2. Limitation values

2.1 These are the parameter limits and maximum allowable concentrations of substances in industrial wastewater before it is discharged into water bodies shown in the table 4 (A.1.1).

2.2 Discharge standards for wastewaters produced by specific industries such as paper, textile or oil industries are specified in a separate standard.

2.3 Industrial wastewaters with values of parameter limits and concentrations of substances equal to or lower than the values specified in column A (table 4 (A.1.1)) may be discharged into the water bodies used as source of domestic water supply.

2.4 Industrial wastewaters with values of parameter limits and concentration of substances lower than or equal to those specified in column B (table 4 (A.1.1)) are discharged only into water bodies used for navigation, irrigation purposes or for bathing, aquatic breeding and cultivation, etc.

2.5 Industrial wastewaters with values of parameter limits and concentrations of substances higher than those specified in the column B, but not exceeding those specified in the column C (table 4 (A.1.1)) are discharged only into specific water bodies permitted by agencies in charge.

2.6 Industrial wastewaters with values of parameter limits and concentrations of substances higher than those specified in the column C (table 4 (A.1.1) shall not be discharged into the environment.

2.7 Standard methods of analysis of parameters and concentrations of substances in industrial wastewater are specified in current Vietnamese Standard*s*.

Table A.1.1 Industrial wastewater discharge parameter limits and maximum allowable concentration of pollutants (TCVN 5945-1995).

No	Parameters and substances	Unit	Limitation values		
			A	B	C
1	Temperature	^{o}C	40	40	45
2	pH value	-	6 to 9	5.5 to 9	5 to 9
3	BOD_5 ($20^{o}C$)	mg/l	20	50	100
4	COD	mg/l	50	100	400
5	Suspended solids	mg/l	50	100	200
6	Arsenic	mg/l	0.05	0.1	0.5
7	Cadmium	mg/l	0.01	0.02	0.5
8	Lead	mg/l	0.1	0.5	1
9	Residual chlorine	mg/l	1	2	2
10	Chromium (VI)	mg/l	0.05	0.1	0.5
11	Chromium (III)	mg/l	0.2	1	2
12	Mineral oil and fat	mg/l	Not	1	5
13	Animal-vegetable fat and fat	mg/l	5	10	30
14	Copper	mg/l	0.2	1	5
15	Zinc	mg/l	1	2	5
16	Manganese	mg/l	0.2	1	5
17	Nickel	mg/l	0.2	1	2
18	Organic phosphorus	mg/l	0.2	0.5	1
19	Total phosphorus	mg/l	4	6	8
20	Iron	mg/l	0.02	5	10
21	Tetrachlorethylene	mg/l	1	0.1	0.1
22	Tin	mg/l	0.2	1	5
23	Mercury	mg/l	0.005	0.005	0.01
24	Total nitrogen	mg/l	30	60	60
25	Trichlorethylene	mg/l	0.05	0.3	0.3
26	Ammonia (as N)	mg/l	0.1	1	10
27	Fluoride	mg/l	1	2	5
28	Phenol	mg/l	0.001	0.05	1
29	Sulfide	mg/l	0.2	0.5	1
30	Cyanide	mg/l	0.05	0.1	0.2
31	Coliform	MPN/100ml	5,000	10,000	-
32	Gross α activity	Bq/l	0.1	0.1	-
33	Gross β activity	Bq/l	1.0	1.0	-

Appendix 1.2 Effluent Requirements in Vietnam according to TCVN 6772-2000

VIETNAM STANDARD **TCVN 6772 – 2000**

The requirements apply to objects that discharge domestic wastewater in areas where there is no central wastewater-treatment plant.

Table A.1.2 Effluent requirements for small-scale wastewater-treatment plants.

Parameter	Unit	Level 1	Level 2	Level	Level 4	Level 5
1 pH		5-9	5-9	5-9	5-9	5-9
2 BOD	mg/l	30	30	40	50	200
3 TSS	mg/l	50	50	60	100	100
4 Settleable solids	mg/l	0.5	0.5	0.5	0.5	n.v.
5TDS	mg/l	500	500	500	500	n.v.
6 Sulphur (as H_2S)	mg/l	1.0	1.0	3.0	4.0	n.v.
7 Nitrate (NO_3^-)	mg/l	30	30	40	50	n.v.
8 Oil and fat	mg/l	20	20	20	20	100
9 Phosphate ($PO_4^{3--)}$	mg/l	6	6	10	10	n.v.
10 Total coliforms	MPN/ 100 ml	1,000	1,000	5,000	5,000	10,000

n.v. = no value indicated

Table A.1.3 Classification of objects amenable to small-scale wastewater-treatment plants (TCVN 6772:2000).

Object	Specification	Required treatment level	Remarks
Hotel	< 60 rooms	Level 3	
	60- 200 rooms	Level 2	
	> 200 rooms	Level 1	
Guesthouse	From 10 to 50 rooms	Level 4	
	50 – 250 rooms	Level 3	
	> 250 rooms	Level 2	
Small hospital	From 10 – 30 beds	Level 2	
	> 30 beds	Level 1	
Large hospital		Level 1	
Office	From 5000- 10000 m^2	Level 3	The surface relates to the working area
	10000 – 50000 m^2	Level 2	
	> 50000 m^2	Level 1	
School/ research facility	From 5000 – 25000 m^2	Level 2	
	> 25000 m^2	Level 1	

Table A.1.3 (continued) Classification of objects amenable to small-scale wastewater-treatment plants (TCVN 6772:2000).

Object	Specification	Required treatment level	Remarks
Shopping mall	From 5000 – 25000 m^2	Level 2	
	> 25000 m^2	Level 1	
Fresh food market	From 500 – 1000 m^2-	Level 4	
	From 1000 to 1500 m^2	Level 3	
	From 1500 to 25000 m^2	Level 2	
	> 25000 m^2	Level 1	
Restaurant	< 100 m^2	Level 5	The surface relates to the dining rooms
	From 100 to 250 m^2	Level 4	
	From 250 to 500 m^2	Level 3	
	From 500 to 2500 m^2	Level 2	
	> 2500 m^2	Level 1	
Apartment building	< 100 apartments	Level 3	
	100 – 500 apartments	Level 2	
	> 500 apartments	Level 1	

Appendix 1.3 Effluent Requirements in Vietnam according to TCVN 5945 – 2005

VIETNAM STANDARD	**TCVN 5945 – 2005**

INDUSTRIAL WASTEWATER STANDARD FOR DISCHARGE

TCVN 5945: 2005 substitutes the TCVN 5945: 1995, TCVN 6980: 2001, TCVN 6981: 2001, TCVN 6982: 2001, TCVN 6983: 2001, TCVN 6984: 2001, TCVN 6985: 2001, TCVN 6986: 2001, TCVN 6987: 2001.

1. Scope

1.1 This standard specifies parameter limits and allowable concentrations of pollutants in wastewater from manufacturing, processing, commercial, and service businesses (in general industrial wastewater).

1.2 This standard is applied to control the quality of industrial wastewater discharged into receiving waters that are used as a source of domestic water, as source of water for purposes needing a water quality lower than domestic water, and into other receiving waters.

2. Limitation values

2.1 At discharge into receiving waters, the parameter limits and concentrations of the contaminants in industrial wastewater must not exceed the values regulated in table 1 (A.1.4).

2.2 Industrial wastewater can be discharged into the receiving waters used as source of domestic water if the parameters and concentrations of the contaminants are equal to or lower than the value stipulated in column A.

2.3 Industrial wastewater, in which parameters and concentrations of the contaminants are higher than the values stipulated in column A, but lower than or equal to the value stipulated in column B, can be discharged into any receiving water other than the receiving waters stipulated in column A.

2.4 Industrial wastewater, in which parameters and concentrations of the contaminants are higher than the values stipulated in column B, but do not exceed the values in column C, can only be discharged into the specifically appointed receiving waters (for example separate wastewater reservoirs and sewer systems leading to wastewater-treatment plants).

2.5 Industrial wastewater with specific compositions is regulated by particular standards.

2.6 The method of collecting samples, analysis and calculation for each defined parameter and concentration of the contaminants is stipulated in the current TCVN or by the authorized agencies.

Table A.1.4 Industrial wastewater discharge parameter limits and maximum allowable concentration of pollutants (TCVN 5942-2005). [Changes in comparison with the standard TCVN 5945-1995 (Appendix A.1.1 of this thesis) are in **bold** letters].

	Parameters	Unit	Limitation values		
			A	B	C
1	Temperature	-	40	40	45
2	pH	-	6 – 9	5.5 – 9	5 - 9
3	Odor	-	Not offensive	Not offensive	-
4	Color, Co-Pt at pH=7	-	20	50	-
5	BOD_5 (20 ^oC)	mg/l	**30**	50	100
6	COD	mg/l	50	**80**	400
7	TSS	mg/l	50	100	200
8	Arsenic (As)	mg/l	0.05	0.1	0.5
9	Mercury	mg/l	0.005	0.01	0.01
10	Lead (Pb)	mg/l	0.1	0.5	1
11	Cadmium (Cd)	mg/l	0.005	0.01	0.5
12	Chromium (VI)	mg/l	0.05	0.1	0.5
13	Chromium (III)	mg/l	0.2	1	2
14	Copper (Cu)	mg/l	**2**	**2**	5
15	Zinc (Zn)	mg/l	**3**	**3**	5
16	Nickel (Ni)	mg/l	0.2	**0.5**	2
17	Manganese (Mn)	mg/l	**0.5**	1	5
18	Iron (Fe)	mg/l	**1**	**5**	**10**
19	Tin (Sn)	mg/l	0.2	1	5
20	Cyanide	mg/l	**0.07**	0.1	0.2
21	Phenol	mg/l	**0.01**	**0.5**	**0.2**
22	Mineral oil and grease	mg/l	**5**	**5**	**10**
23	Vegetable oil and fat	mg/l	**10**	**20**	**30**
24	Residual chlorine	mg/l	1	2	-
25	**PCBs**	mg/l	0.003	0.01	0.05
26	**Org. phosphate pesticides**	mg/l	0.3	1	-
27	**Org. chlorine pesticides**	mg/l	0.1	0.1	-
28	Sulfide	mg/l	0.2	0.5	1
29	Fluoride	mg/l	5	10	15
30	**Chloride**	mg/l	500	600	1000
31	**Ammonia (NH_3- N)**	mg/l	**5**	**10**	**15**
32	Total nitrogen (total-N)	mg/l	**15**	**30**	60
33	Total phosphorus	mg/l	4	6	8
34	Coliform	MPN/100 ml	5,000	**5,000**	-
35	**Bioassay**		90% survival of fish after being 96 hours in 100% wastewater		
36	Total radioactivity α	Bq/l	0.1	0.1	-
37	Total radioactivity β	Bq/l	1.0	1.0	-

Annex to TCVN 5945-2005

Explanation of the coefficient of discharge flow (K_f), coefficient of flow-rate/ volume of receiving water (K_q) and method of calculation of the maximum allowed concentration of the contaminants in industrial wastewater.

1 Formula for the calculation of maximum allowed concentration of contaminants in industrial wastewater:

a The maximum allowed concentration of the contaminants in wastewater from manufacturing, processing, commercial and service businesses is calculated with the equation:

$C_{max} = C \times K_q \times K_f$

In which:

C_{max} (mg/l): maximum allowed concentration of the contaminants in wastewater from manufacturing, processing, commercial and service businesses, discharging into the receiving waters.

C (mg/l): maximum allowed value of the concentration of the contaminants as stipulated in TCVN 5945:2005

K_q : coefficient of flow-rate/volume of receiving water;

K_f : coefficient of capacity of discharging source.

b The abovementioned equation for calculation of the maximum allowed concentration of contaminants in industrial wastewater is not applied for column C and parameters which are described in Table 1 of TCVN 5945:2005 with the numbers 1 to 4, and 34 to 37.

2 Coefficient value K_q

a The coefficient value K_q for *rivers as receiving water* is given in Table 1B.

Table 1B: Coefficient value K_q as function of the flow-rate of rivers used as receiving waters.

River flow (m^3/s)	Value K_q
$Q \leq 50$	0.9
$50 < Q \leq 200$	1
$Q > 200$	1.1

Q is the flow-rate of rivers that serve as wastewater receptors. Q is calculated as average value for the three driest months during three constant years (information obtained from the Center of National Hydrometeorology). K_q = 0.9 where there is no information of the flow from a small canal, stream, or ditch.

b The coefficient value K_q for *lakes as receiving water* is given in Table 2B.

Table 2B: Coefficient value K_q as function of the volume of lakes as receiving waters.

Volume of a lake as receptor (10^6 m^3)	Value K_q
$V \leq 10$	0.6
$10 < V \leq 100$	0.8
$V > 100$	1.0

The volume V is the volume of the lake as collector of wastewater. V is calculated as average value for the three driest months during three constant years (information from the Center of National Hydrometeorology).

c The coefficient value K_q = 1.2 is applicable where the sea shore area serves as effluent collector. The coefficient value K_q = 1 is applicable where the sea shore area is used as ecological preservation area, for purposes like sports or underwater entertainment.

3 Coefficient value K_f

The coefficient value K_f is given in table 3B.

Table 3B: Coefficient value K_f as function of the flow-rate of the discharging sources.

Flow-rate of the discharging source (m^3/24h)	Value K_f
$F \leq 50$	1.2
$50 < F \leq 500$	1.1
$500 < F \leq 5000$	1.0
$F > 5000$	0.9

4 The application regulation for new parameters of contaminants, and stricter parameters for the manufacturing, processing, commercial and service businesses which are already in operation.

January 1, 2008 is the deadline for enterprises to apply new parameters with the numbers 3, 4, 25, 27, 30, 35 in Table 1 TCVN 5945: 2005.

The parameters for which stricter requirements apply are: COD (column B), cadmium and nickel (column B), and total Nitrogen. For the parameter of Coliform temporarily the value regulated in table 1 TCVN 5945 : 1995 is applied.

January 1, 2008 is the deadline for all manufacturing, processing, commercial and service businesses to apply TCVN 5945 : 2005, the coefficient of volume/ flow of the receiving water (K_q) and the coefficient of flow-rate of the discharging sources (K_f).

APPENDIX 2 CURRENCY CONVERSION

The currencies USD, Dutch guilder, Euro and Vietnamese Dong (VND) utilized in this thesis were converted using the table A.2.1.

Table A.2.1 Exchange rates of from USD to Dutch guilder, Euro and Vietnamese Dong (VND).

Year	USA (USD)	Netherlands[2] (Dfl/Euro)	Vietnam[3] (VND)
1991	1	1.87	n.a.
1992	1	1.76	10,520
1993	1	1.86	10,840
1994	1	1.81	11,040
1995	1	1.60	11,000
1996	1	1.68	11,140
1997	1	1.95	12,290
1998	1	1.98	13,880
1999	1	2.07	14,030
2000	1	2.39	14,510
2001	1	2.46	15,083[4]
2002	1	0.95	15,402
2003	1	0.79	15,645
2004	1	0.76	15,776
2005	1	0.84	15,913
2006	1	0.76	16,051
2007	1	0.68	16,010
2008	1	0.72	17,494
2009	1	0.70	18,361

[2] Conversions of USD to Dutch guilder (Dfl): http://www.dnb.nl/dnb/home/file/sn2003m10_tcm46-147401.pdf. Conversions of USD to Euro (per 31 of December of the mentioned year): www.bankofcanada.ca. (last accessed on June 14, 2010). The Euro was introduced in The Netherlands as banknotes and coins on January 1, 2002.
[3] Vietcombank, exchange rate at December 31 of the given year.
[4] Data from 2001-2006 on www.vietcombank.com.vn (last visited on September 22, 2008).

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