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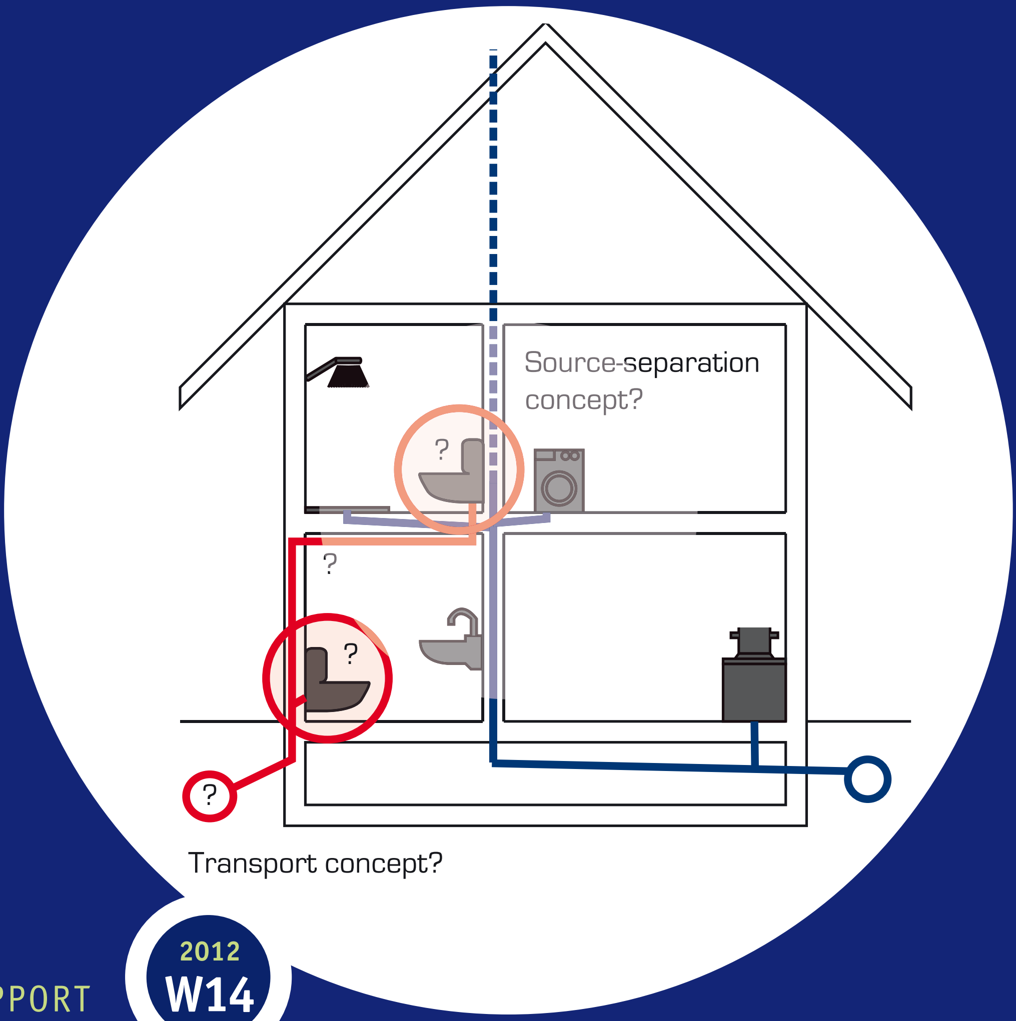
SOURCE-SEPARATION IN THE URBAN WATER INFRASTRUCTURE



RAPPORT

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W14

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STOWA IN BRIEF

The Foundation for Applied Water Research (in short, STOWA) is a research platform for Dutch water controllers. STOWA participants are all ground and surface water managers in rural and urban areas, managers of domestic wastewater treatment installations and dam inspectors.

The water controllers avail themselves of STOWA's facilities for the realisation of all kinds of applied technological, scientific, administrative legal and social scientific research activities that may be of communal importance. Research programmes are developed based on requirement reports generated by the institute's participants. Research suggestions proposed by third parties such as knowledge institutes and consultants, are more than welcome. After having received such suggestions STOWA then consults its participants in order to verify the need for such proposed research.

STOWA does not conduct any research itself, instead it commissions specialised bodies to do the required research. All the studies are supervised by supervisory boards composed of staff from the various participating organisations and, where necessary, experts are brought in.

The money required for research, development, information and other services is raised by the various participating parties. At the moment, this amounts to an annual budget of some 6,5 million euro.

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PREFACE

Human pharmaceuticals have been observed in wastewater, surface water, infiltrated surface water, and sporadically also in drinking water. This report assembles knowledge on sources, occurrence, removal technologies and effects of pharmaceuticals in the (Dutch) water cycle and defines knowledge gaps.

The investigation reveals that the fraction of the consumed human pharmaceuticals that enters surface waters enables prediction of annual loads in surfacewaters since there is sufficient knowledge on consumption, metabolism by the human body and removal by wastewater treatment. Effect studies suggest that pharmaceuticals are able to affect aqueous ecosystems while human health effects are currently not expected.

The investigation also reveals several knowledge gaps. There is currently limited information on the formation and effects of transformation products of pharmaceuticals. Furthermore the combined effects of complex of pharmaceuticals and other microcontaminants in the aqueous are largely unknown. Additionally, the cost benefit ratio of variable technological tools that reduce pharmaceuticalsv in the watercycle has not been assessed.

Despite potential ecological effects, unwanted presence in drinking water, available techniques to remove pharmaceuticals from water and the avaialbility of provisional guideline values there is currently no structured international cooperation on monitoring and legislation.

ABSTRACT

In the Netherlands, combined collection systems are normally used for the collection of black water and grey water *inside* buildings. This domestic wastewater flow is subsequently transported towards a treatment facility. Depending on the sewer system *outside* buildings, domestic wastewater is mixed with storm water prior to treatment. Over the past years, several new concepts have been proposed and several initiatives have been taken aiming at a more sustainable system of wastewater collection and treatment. Alternative sanitation systems are generally advocated based on (1) their potential contribution to energy savings, (2) potential recovery of nutrients from domestic waste streams, and (3) potential removal of micropollutants present in domestic wastewater. Source-separated sanitation systems are one flavour to alternative sanitation systems.

The fact that the existing urban water infrastructure is designed for combined collection and transport of black and grey water (and possibly storm water) complicates the separate treatment of black water in the existing building infrastructure. However, the efforts required for the renovation and rehabilitation of the existing urban water infrastructure on the short term are substantial. This is a key chance for the implementation of alternative transport concepts *outside* buildings. On the other hand, renovation works within existing buildings or redevelopment of whole residential or commercial neighbourhoods are key chances for the implementation of alternative collection concepts *inside* buildings.

Previous and on-going research on source-separated collection and treatment so far has mainly focused on the treatment of separated streams, and pilot projects were limited to new building projects for the most part. Relatively little attention has been given to the existing building infrastructure. Furthermore, treatment options have received far more attention than the collection and transport, with the exception of vacuum collection. The focus of this report therefore lies on civil engineering aspects of separate collection and transport of black water.

This report sheds light on the potential for separate collection and transport of black water in the existing building infrastructure by means of conventional drainage concepts and modes of transport on the one hand, and ideas based on thinking *outside* the box on the other hand. Generally speaking, separation of streams can be either spatial or temporal or a combination thereof, and initial separation can take place *inside* or *outside* buildings. The concepts presented in this report cover both of these approaches. Thereby, the main guiding principle was to look for concepts with minimal structural changes *inside* existing buildings and concepts that possibly still make use of the existing urban water infrastructure *outside* buildings.

This report suggests that integration of source-separated collection and transport is thinkable and discussable in the existing urban water infrastructure. Yet the concepts exposed in this report are at different stages as to their state of maturity and implementation. Whereas some are merely theoretical concepts, others have already been shown to be practically feasible.

There are good reasons to rethink the urban water infrastructure, and obviously there are plenty of opportunities for implementing more flexible alternative sanitation systems. However, a number of open questions remain to be answered. It is suggested that the further development of alternative sanitation concepts take an integral view on wastewater management, rather than separately thinking about toilet, sewer system, and wastewater treatment. To achieve this, it is important that urban drainage experts work alongside wastewater treatment experts in the development of alternative concepts.

SAMENVATTING

In Nederland wordt zwart en grijs water doorgaans gemengd ingezameld voordat het naar een zuiveringsinstallatie wordt getransporteerd. Onderweg wordt deze huishoudelijke afvalwaterstroom – afhankelijk van het rioleringssysteem – vaak ook nog gemengd met regenwater. In de afgelopen jaren zijn diverse nieuwe concepten ontwikkeld en initiatieven ontplooid om tot een duurzamer systeem voor de inzameling en verwerking van afvalwater te komen. Vaak genoemde pluspunten van deze nieuwe sanitatieconcepten zijn: (1) ze kunnen een bijdrage leveren aan energiebesparing, (2) ze bieden de mogelijkheid nutriënten terug te winnen uit huishoudelijke afvalwaterstromen, en (3) ze bieden de mogelijkheid microverontreinigingen te verwijderen uit huishoudelijk afvalwater. Brongescheiden sanitatie is een van de mogelijkheden op dit vlak.

Het feit dat het huidige afvalwatersysteem in stedelijk gebied is ingericht op gemengde inzameling en transport van zwart en grijs water (en vaak ook regenwater), maakt het lastig zwart water in de bestaande bebouwing afzonderlijk te verwerken. Er zal op korte termijn echter aanzienlijk moeten worden geïnvesteerd in onderhoud en renovatie van het huidige afvalwatersysteem. Dit biedt belangrijke kansen voor de invoering van nieuwe transportsystemen. Daarnaast vormen renovatiewerkzaamheden in bestaande gebouwen en modernisering van complete woonwijken en bedrijventerreinen een uitgelezen kans voor de invoering van nieuwe inzamelingssystemen.

Onderzoek op het gebied van brongescheiden sanitatie heeft tot nu toe – met uitzondering van vacuüminzameling – veel meer aandacht besteed aan verwerking van gescheiden afvalwaterstromen dan aan inzameling en transport. Verder heeft het grootste deel van de pilotprojecten plaatsgevonden in nieuwbouw en is er nog relatief weinig aandacht besteed aan bestaande bebouwing. Dit rapport wil die lacune aanvullen en belicht daarom de mogelijkheden voor gescheiden inzameling en transport van zwart water in bestaande bebouwing door middel van conventionele inzamelings- en afvoersystemen aan de ene, en innovatieve concepten aan de andere kant.

Globaal bekeken, kunnen stromen gescheiden worden in ruimte of tijd of een combinatie daarvan, en de eerste scheiding kan zowel binnen als buiten gebouwen plaatsvinden. Beide benaderingen komen in de besproken concepten aan bod. Het uitgangspunt was met name te zoeken naar systemen waarvoor binnen bestaande gebouwen zo weinig mogelijk structurele veranderingen hoeven te worden aangebracht en systemen die buiten gebouwen mogelijk gebruik kunnen blijven maken van het huidige afvalwatersysteem.

Volgens dit rapport is integratie van gescheiden inzameling en transport in het huidige afvalwatersysteem denkbaar en bespreekbaar. De in dit rapport besproken systemen bevinden zich qua uitwerking en implementatie echter in verschillende stadia. Terwijl sommige zich nog in een theoretisch stadium bevinden, is van andere al aangetoond dat ze in de praktijk bruikbaar zijn.

Er is voldoende aanleiding voor een herziening van het stedelijk afvalwatersysteem, en het is duidelijk dat er meer dan genoeg mogelijkheden zijn voor invoering van nieuwe, flexibelere sanitatiesystemen. Een aantal vragen dient echter nog te worden beantwoord. Bij de verdere ontwikkeling van nieuwe sanitatie verdient bovendien een integrale benadering van afvalwaterbeheer de voorkeur boven afzonderlijk nadenken over toilet, rioleringssysteem en afvalwaterverwerking. Om daartoe te komen, is het belangrijk dat deskundigen op het vlak van inzameling en transport van afvalwater en deskundigen op het vlak van afvalwaterzuivering samenwerken aan het ontwikkelen van nieuwe systemen.

VOORUITBLIK

Vaak genoemde pluspunten van nieuwe sanitatieconcepten zijn: (1) ze kunnen een bijdrage leveren aan energiebesparing, (2) ze bieden de mogelijkheid nutriënten terug te winnen uit huishoudelijke afvalwaterstromen, en (3) ze bieden de mogelijkheid microverontreinigingen te verwijderen uit huishoudelijk afvalwater. Brongescheiden sanitatie is een van de mogelijkheden op dit vlak. Eerder in dit rapport werd al aangegeven dat onderzoek op het gebied van brongescheiden sanitatie zich tot nu toe hoofdzakelijk heeft gericht op de verwerking van gescheiden afvalwaterstromen en dat het grootste deel van de pilotprojecten heeft plaatsgevonden in nieuwbouw. Dit rapport stelt echter dat het ook denkbaar en bespreekbaar is gescheiden inzameling te integreren in het huidige stedelijk afvalwatersysteem. Hierbij moet wel worden vermeld dat de in dit rapport besproken systemen zich qua uitwerking en implementatie in verschillende stadia bevinden. Sommige bevinden zich nog in een theoretisch stadium, terwijl van andere al is aangetoond dat ze in de praktijk bruikbaar zijn. Om verdere vooruitgang te kunnen boeken met scheiding van stromen binnen het huidige afvalwatersysteem, en met nieuwe sanitatiesystemen in het algemeen, zal een aantal vragen en aspecten onder de loep genomen moeten worden.

PRIKKELS EN KANSEN VOOR INVOERING

Er zijn twee belangrijke groepen prikkels die invloed hebben op het tempo waarin nieuwe sanitatiesystemen kunnen worden ingevoerd.

De eerste belangrijke groep prikkels bestaat uit de wettelijke en maatschappelijke eisen die aan afvalwaterbeheer worden gesteld. Met het oog op de oppervlaktewaterkwaliteit is de huidige trend rwzi's te verplichten tot tertiaire zuivering, met als doel de hoeveelheid vervuilende stoffen in het effluent verder terug te dringen. Hoog op de politieke agenda staan ook energiewinning en klimaatneutraal afvalwaterbeheer. Verder is het heel goed mogelijk dat de wens om nutriënten (fosfor) terug te winnen uit afvalwaterstromen en de behoefte een oplossing te vinden voor het probleem van microverontreiningen (met name hormonen, medicijnen en medicijnresten) in de toekomst ook belangrijke prikkels voor de invoering van nieuwe sanitatiesystemen worden.

De tweede belangrijke groep prikkels wordt gevormd door de noodzaak van optimalisatie en modernisering van bestaande stedelijke gebieden en/of het huidige afvalwatersysteem. Hierin zal op korte termijn flink moeten worden geïnvesteerd. De noodzaak het rioleringssysteem aan te pakken wordt plaatselijk nog urgenter vanwege de bodemgesteldheid, die in een groot deel van Nederland sowieso de belangrijkste prikkel tot rioolrenovaties is. De ophanden zijnde optimalisatie en modernisering van gemeentelijke rioleringssystemen is de kans bij uitstek voor de invoering van nieuwe transportsystemen. Daarnaast vormen renovatiewerkzaamheden in bestaande gebouwen en modernisering van complete woonwijken en bedrijventerreinen een uitgelezen kans voor de invoering van nieuwe inzamelingssystemen.

IMPLICATIES VOOR HET SANITATIESYSTEEM

Modernisering van bestaande stedelijke afvalwatersystemen en integratie van nieuwe concepten zal hoogstwaarschijnlijk leiden tot een diversificatie van waterafvoersystemen en tot oplossingen die flexibeler zijn in ruimte en tijd. Zoals Berlamont (2004) al aangaf, zullen er in de toekomst geen algemene richtlijnen meer zijn die gelden voor alle stedelijke waterafvoersystemen, maar zal veel meer rekening moeten worden gehouden met plaatselijke kenmerken en beperkingen. Het zal duidelijk zijn dat er voldoende aanleiding is om het stedelijk afvalwatersysteem te herzien en dat er meer dan genoeg mogelijkheden zijn voor de invoering van nieuwe, flexibelere sanitatiesystemen. Maar zijn we daar ook klaar voor?

ONDERZOEKSVRAGEN

Er zijn bijna even veel vragen die nog beantwoord dienen te worden en mogelijkheden voor verder onderzoek als mogelijkheden voor veranderingen aan het systeem. Algemene onderzoeksvragen betreffen de doeltreffendheid en wenselijkheid van brongescheiden sanitatie:

- Zijn bronscheidingssystemen effectief en efficiënt met het oog op een aantal functionele doelen (zoals terugwinning van nutriënten, verwijdering van microverontreinigingen, flexibiliteit)?
- Zijn er andere nieuwe sanitatiesystemen of aanpassingen aan conventionele systemen denkbaar die net zo effectief en efficiënt zijn? Of zelfs effectiever en efficiënter?

Specifiekere onderzoeksvragen betreffen de technische implementatie van de geopperde bronscheidingssystemen en de evaluatie daarvan:

- Hoe zouden de verschillende onderdelen van een specifiek bronscheidingssysteem (zoals toiletaansluitingen en riool-huisaansluitingen) eruit moeten zien?
- Hoe kunnen verschillende evaluatiecriteria (zoals gebruiksgemak, kans op defecten, systeemprestaties e.d.) worden gemeten en uitgedrukt?

Met betrekking tot gescheiden inzameling en verwerking van zwart water in het bijzonder doen de volgende onderzoeksvragen zich voor:

- Hoe worden de eigenschappen van het zwarte water (op het vlak van transporteerbaarheid en verwerkbaarheid) beïnvloed door het type toilet en de manier waarop het wordt gebruikt, het type inzamelingssysteem ter plaatse en het type transportsysteem naar een (semi-gecentraliseerde) zuiveringsinstallatie?
- In welke mate is er een samenhang tussen ontwerp van de voorzieningen binnenshuis, inzamelings- en transportmethoden, en zuiveringssystemen?

Vanwege het onregelmatige karakter van de zwartwaterproductie is ook onderzoek op het vlak van schaalgrootte gewenst (de zwartwaterproductie van een huishouden kan bijvoorbeeld groot zijn tijdens een feestje, maar nihil tijdens de zomervakantie). De onderzoeksvraag die hieruit voortvloeit, luidt derhalve:

- Op welke schaal moet worden gewerkt om zwart water adequaat te kunnen inzamelen, transporteren en zuiveren gezien de variaties in zwartwaterproductie gedurende een etmaal, week en seizoen?

Een deel van deze vragen kan worden beantwoord vanachter het bureau. Voor een ander deel zullen pilotprojecten moeten worden uitgevoerd.

AANBEVELINGEN

1. Het valt aan te bevelen om scheiding van afvalwaterstromen binnen het bestaande stedelijk afvalwatersysteem serieus te overwegen als mogelijkheid.
2. Het is belangrijk in te springen op de kansen voor invoering van dergelijke systemen die zich voordoen tijdens de modernisering van het stedelijk afvalwatersysteem.
3. Bij de verdere ontwikkeling van nieuwe sanitatie verdient een integrale benadering van afvalwaterbeheer de voorkeur boven afzonderlijk nadenken over toilet, rioleringssysteem en afvalwaterverwerking. Om daartoe te komen, is het essentieel dat deskundigen op het vlak van inzameling en transport van afvalwater en deskundigen op het vlak van afvalwaterzuivering samenwerken aan het ontwikkelen van nieuwe systemen. In het ideale geval zal het oplossen van transportgerelateerde kwesties in nieuwe systemen tegelijkertijd licht werpen op transportgerelateerde problemen in de bestaande conventionele sanitatiesystemen.
4. Flexibiliteit van het systeem is een belangrijke dimensie in de ontwikkeling van nieuwe sanitatiesystemen. Een flexibel systeem is namelijk sneller aan te passen aan veranderende eisen en beperkingen gesteld aan het stedelijk afvalwatersysteem.

SOURCE-SEPARATION IN THE URBAN WATER INFRASTRUCTURE

CONTENTS

1

INTRODUCTION

The idea of source-separated collection of different types of domestic wastewater has emerged at the end of the 20th century and various research projects and pilot projects have been carried out throughout the past two decades both in the Netherlands and elsewhere1. An overview on various pilot projects in the Netherlands, Germany and Sweden is provided in, for example, STOWA 2005-13.

Research so far has mainly focused on the treatment of separated streams, and pilot projects were limited to sustainable new building projects for the most part. Little attention was paid to the integration of source-separated collection in the existing urban water infrastructure and the transport of source-separated streams from the point of collection to the treatment facility. The general aim of this report is to shed light on these forgotten aspects of source-separation from the perspective of the Dutch context. This first chapter starts with an overview on the framework of wastewater management. Thereafter the scope of this research is defined more in detail and the structure of this report is explained.

1.1. FRAMEWORK

Water is an essential element of life and is used for many different domestic and industrial purposes. Upon its use water normally turns into wastewater. Water used in kitchens, laundry rooms, lavatories, bathrooms, toilets and similar facilities is normally referred to as domestic wastewater and is collected from various domestic sanitary appliances. In the domestic context, wastewater management starts at this point.

On the one hand, approaches to wastewater management are changing over time, thereby reflecting the state of technology, the state of mind of society, and the goals and objectives formulated in the legislative and policy framework. On the other hand, the presence or absence of certain constituents and the respective concentrations thereby considerably influence further treatment possibilities and necessities as well as possibilities for resource recovery and reuse of residual products from wastewater treatment. A brief discussion of the constituents of domestic wastewater and the development of wastewater management over the past century shall clearly point out why the idea of source-separated collection emerged in the first place.

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1 It is important to point out that source-separation as a concept does not only involve the separation of particular streams, but also the combination of specific streams (e.g., organic kitchen waste and black water).

1.1.1. CONSTITUENTS OF DOMESTIC WASTEWATER

The use of water normally results in the addition of gases, liquids and solids to the previously clean water. The wastewater streams thus formed essentially enter the domestic drainage system via sanitary appliances during the usage of water. Furthermore, domestic drainage systems can be misused as waste discharge system, and liquids or solids may be introduced without necessarily using water. The liquids and solids introduced into the drainage system comprise of a number of individual constituents.

Constituents of interest in domestic wastewater include water, energy, organic matter, nutrients, heavy metals, pathogens, and organic micropollutants. The interest in a certain constituent or group of constituents can thereby be grounded on resource reuse and/or on concerns about adverse effects related to a certain constituent (e.g., health risks, environmental pollution, eco-toxicity).

Possible sources of constituents of interest in domestic wastewater include but are not limited to humans, drinking water, piping, welds, alimentation, personal care products, pharmaceuticals, detergents, and any other liquids or solids that are disposed of via the drainage system (e.g., oil and grease, paint and solvents, cat litter).

Of the constituents of interest, substantial fractions are found in the black water fraction of domestic wastewater. Nutrients, pharmaceutical and pharmaceutical residues, and faecal pathogens are mostly found in the black water fraction. A selection of constituents of interest is discussed more in detail in Appendix A.

1.1.2. EVOLUTION OF WASTEWATER MANAGEMENT

This paragraph shall briefly summarise the shift in goals and the related changes to wastewater management since the 19th century. Beyond doubt, advanced practices for the collection and removal of human excreta from urban settlements date back several millennia but the knowledge and skills involved were lost for the most part after the fall of the Roman Empire (Novotny et al., 2010).

THE NEED FOR HYGIENIC SANITATION

In the 19th century, the catastrophic hygienic situation in many European cities and related epidemics gave rise to the introduction of collection of human excreta from cesspits and privies (night soil system). Later on, increasing demand for fertiliser in the agricultural sector led to a lively trade with human excreta and provided the basis for the economic feasibility of other collection systems, such as for example the Liernur vacuum collection system applied in several cities in the Netherlands and elsewhere by the beginning of the 20th century.

THE RISE OF WATER-BORNE SANITATION

Increasing availability of household water supplies and the introduction of water closets resulted in a dilution of human excreta with water and the production of considerable amounts of wastewater. Storage and collection for agricultural use was no longer practicable and hygienic conditions were impaired as wastewater was discharged to the gutters so far used for the discharge of grey water and rainwater. The introduction of flush sewer systems was the reaction to this development. Opponents of water-borne sanitation criticised that valuable resources were wasted and that soils would degrade without human excreta as organic fertiliser. But the advent of industrial production of inexpensive mineral fertiliser in the first half of the 20th century weakened these arguments. Throughout most of the 20th century, night soil systems, vacuum systems and water-borne sanitation existed in parallel, though with a clear trend towards water-borne sanitation. The last Dutch municipalities to completely abandon the night soil system were Zaandam in 1979 and Alkmaar in 1983 (Vis, 1996). The last operative Liernur vacuum system was decommissioned in Trouville sur Mer (France) in 1987 after 95 years of operation (Eau Québec, 1994).

PROBLEM SOLVED = PROBLEMS CREATED

The introduction of water-borne sanitation was successful with respect to its positive contribution to public health. Furthermore, flush sewer systems were often designed to facilitate drainage of storm water along with domestic wastewater. Such combined sewer systems hence also contributed to the prevention of flooding in urban areas. Yet water-borne sanitation created new problems wherever wastewater was discharged to surface water bodies. Visual impairment, oxygen depletion and eutrophication were the most evident results of water-borne sanitation. The invention of the activated sludge process in 1913 was the first step towards biological treatment of wastewater and has been improved ever since. Still, wastewater treatment plants were not immediately widespread. In many European countries, this process is still under way and substantial percentages of the population were still not connected to a wastewater treatment plant as recently as a decade ago (COM, 2004).

But even a comprehensive introduction of wastewater treatment plants likely would not fully solve the problems as other alarming impacts of water-borne sanitation emerged over the past years. On the one hand, micropollutants are discharged to surface water bodies and pose a serious threat on the aquatic environment and drinking water sources. On the other hand, current wastewater management results in broken nutrient cycles. Summing up, several problematic points of water-borne sanitation remain to this day despite technical advances through the last decades: emission of nutrients and micropollutants to surface water bodies via the effluent, emission of methane from sewer systems, frequent discharge of untreated wastewater to surface water bodies via central sewer overflows (CSOs), handling of residual sludge, and the need for substantial renovation of large parts of the network as well as its extension (STOWA 2005-12).

(UN)SUSTAINABILITY OF CURRENT WASTEWATER MANAGEMENT

Virtually all centralised wastewater treatment plants in the Netherlands are based on the activated sludge process supplemented by biological nutrient removal. Overall, the process is geared towards the production of a high-quality effluent. Nutrients are not routinely recovered but discharged with the effluent, released into the air (nitrogen) or disposed of with the residual sludge (phosphorus). Occasionally, phosphorus is recovered from the residual sludge. Thermal energy is mainly contained in the liquid fraction of wastewater, whereas most of the (recoverable) chemical energy is contained in the solid fraction (i.e., faeces and organic kitchen waste). Thermal energy is to a large extent transferred to the surrounding soil during transport in sewer systems. Chemical energy is partly used by microorganisms in sewer systems for various conversion processes. Of the chemical energy arriving at the treatment plant, a considerable fraction is removed by the activated sludge treatment process, and this removal actually requires the addition of energy for aeration facilities. Of the chemical energy still available in the residual sludge from treatment plants based on the activated sludge process, just under two thirds were recovered in the year 2008 (CBS,
2010; STOWA 2005-W03). The sustainability of centralised systems based on the activated sludge process is increasingly being questioned with regard to energy balance, nutrient flow, the capacity to remove micro pollutants from diluted streams, and the possibility to comply with future stricter regulations.

TOWARDS MORE SUSTAINABLE WASTEWATER MANAGEMENT

Over the past years, several new concepts have been proposed and several initiatives have been taken aiming at a more sustainable system of wastewater collection and treatment. The driving forces behind these initiatives are chances with regard to potential water savings, better use of resources, efficient treatment of new problematic substances, cost savings as well as a contribution to policy goals on energy, environment and climate. Amongst these projects are: separate collection and local treatment of rainwater, wastewater treatment plants as power plants, water reclamation and reuse as process water, improvements in process technology, and source-separated collection and treatment. Local treatment or infiltration of rainwater (afkoppelen) aims at reducing the fraction of rainwater in combined sewer systems, thereby allowing for a more efficient treatment of the remaining wastewater and a reduction of the pollution linked to combined sewer overflows; it is current practice in the Netherlands. Separate collection of rainwater is possible where separate sewer systems are available. Wastewater treatment plants as power plants refers to a concept where wastewater treatment plants are designed to be net energy producers. Water reclamation projects aim at reducing the pressure on drinking water sources. Improvements in process technology normally aim at better energy recovery, less energy demand, better removal efficiencies, removal of new substances, or lower costs. Source-separation refers to concepts where human excreta are collected separate from other domestic wastewater streams. Variations of this concept are separate collection of urine (yellow water), separate collection of faeces (brown water), separate collection of toilet water (black water), and separate collection of both urine (yellow water) and faeces (brown water).

ENTRENCHMENT AND ITS IMPLICATIONS

Implementation of new concepts is comparatively straightforward in new buildings and new residential or commercial neighbourhoods. But adoption of new concepts in the existing infrastructure has to deal with the results of system choices made throughout the past century: municipal and industrial wastewater is often collected together with infiltration and inflow, the wastewater then is transported in large sewer systems towards wastewater treatment plants from where the cleaned effluent is discharged into a surface water body and residual sludge is subjected to further treatment and then incinerated for the most part.

Entrenchment implies that changes to existing systems will likely be gradual. Whereas sewer systems were relatively homogenous until the end of the 20th century, the implementation of separate sewer systems in the last decades and the introduction of local treatment of rainwater led to hybrid systems. This development raised a number of questions pertaining to design, maintenance, management and responsibilities (Who is designing and maintaining what and how?). Further development and local implementation of new trends in wastewater management will contribute to a further diversification of urban drainage systems. As a result, general guidelines applicable for all urban drainage systems will need to be replaced by urban drainage engineering that takes into account local characteristics and limitations (Berlamont, 2004). The guiding principle must be to strive for solutions that best reach the goals set whilst taking into account existing technical, practical and financial limitations. The goals, however, have changed over time and are likely to change further in the near future.

1.2. SCOPE AND APPROACH

This research is based on the presumption that resource recovery and extensive removal of constituents of concern will become a crucial additional goal of future sanitation systems and that existing flow through infrastructure will be replaced by more circular concepts. It is interesting to note that the European Waste Framework Directive (2008/98/EC) clearly states following waste hierarchy: (a) prevention, (b) preparation for re-use, (c) recycling, (d) other recovery (e.g., energy recovery), and (e) disposal. Wastewater, however, is exempted from this directive and neither the European Water Framework Directive (2000/60/EC) nor the European Urban Wastewater Treatment Directive (1991/271/EEC) mentions a similar hierarchy emphasising prevention of water pollution and re-use of resources.

Moreover, it is assumed that there will be a trend towards tailor-made concepts as there will be no single best concept that is generically applicable and appropriate for any combination of given local characteristics and limitations. The technical implementation, however, will likely be standardised to a large extent. The main challenge hence is to determine a reasonable and feasible transition path from conventional infrastructure towards infrastructure that is in line with new goals. Hereby, considerable room is given for creative engineering solutions tailored to local conditions and requirements.

The scope of this research is to shed light on one of the possibilities of integrating new goals into the existing building infrastructure: separate collection and treatment of black water. Black water contains the largest fraction of nutrients in domestic wastewater. Previous and ongoing research on source-separated collection and treatment so far has mainly focused on remote areas and sustainable new housing projects. Little attention has been given to the existing building infrastructure. Furthermore, treatment options have received far more attention than the collection and transport, with the exception of vacuum collection. The focus of this work therefore lies on civil engineering aspects of separate collection and transport of black water. A thorough discussion of the feasibility and sensibility of separate collection, transport of black water in the context of the existing building infrastructure raises a number of specific questions. These can be arranged in three main groups.

(A) Source-separated collection and transport of black water:

1. How is wastewater collected in existing buildings and at which point are black and grey water streams mixed?
2. Which changes can be made to the infrastructure inside and/or outside buildings in order to separately collect black water (or its constituents)?
3. What is the fraction of black water that can be collected separately without major changes to the existing collection system?
4. Which conventional modes of transport are available to transport black water and what are the limiting factors?
5. What are the limiting conditions certain separation concepts and modes of transport impose on the separate treatment of black water?
6. What are the alternatives to conventional separation concepts and modes of transport and what are potential limitations?

(B) Evaluation of possible concepts for the separate collection and treatment of black water in the existing infrastructure:

7. What are the functional requirements for sanitation in the Netherlands?
8. What are possible scenarios for the separate collection and treatment of black water in the existing building infrastructure?
9. Do these scenarios meet the functional requirements?
10. What are key advantages and drawbacks of the scenarios at hand?
11. What about the acceptance by the general public?
12. How vulnerable and resilient are the scenarios at hand what are the consequences in case of system or component failure?
13. What are the treatment and recovery efficiencies?
14. What are the fractions of recovery and disposal?
15. How does the energy balance look like?

(C) Open questions and research opportunities:

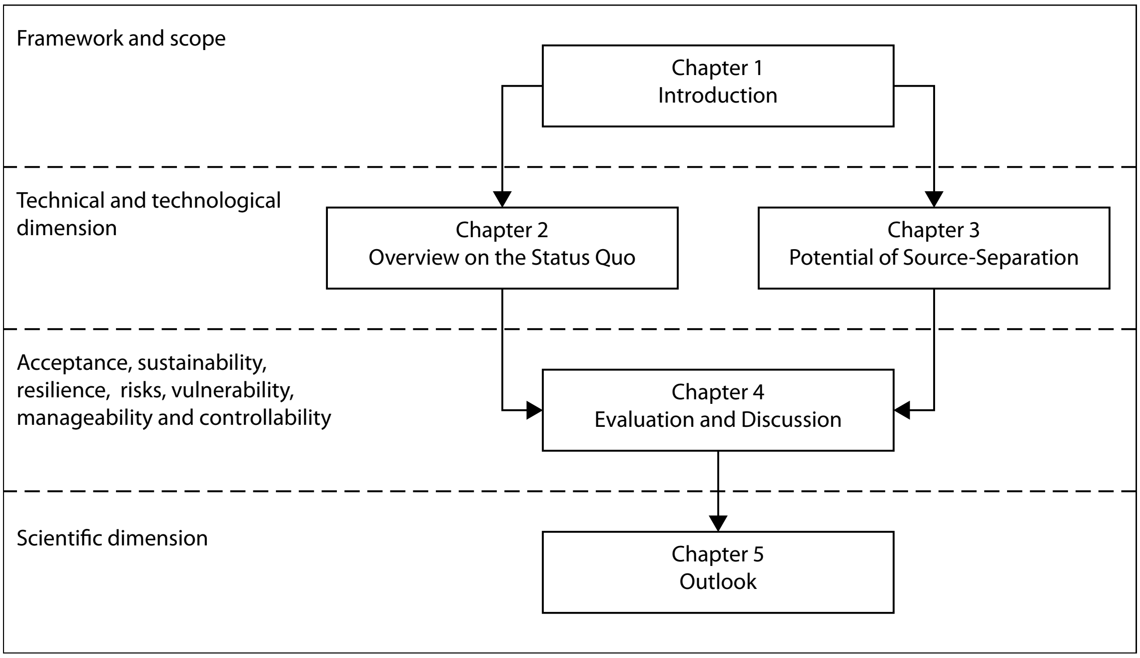
16. What and where are the uncertainties and which type of research is required to answer open questions?
17. Which are good settings for further research and pilot projects?

Given that a thorough discussion of several of above questions could fill a report on its own, this report does not aim at comprehensively answering all of above questions. Rather, this report aims at providing food for thought by exposing a first treatise on source-separation in the existing building infrastructure and partially answering some of the above questions, thereby raising new, related questions and pointing out important factors and aspects as well as directions for future research.

1.3. READER'S GUIDE

The structure of the report roughly follows above questions. Chapter 2 will provide a brief overview on conventional drainage concepts and modes of transport from a general perspective. Chapter 3 shall investigate the potential of source-separation in the existing infrastructure and expose possibilities and limitations with regard to the separate transport of black water. Chapter 4 discusses functional requirements for sanitation and evaluation criteria for both the current situation as well as new concepts. Furthermore, resource recovery and pollution prevention are discussed in a broader context. Chapter 5 presents an outlook on possible further steps as well as further research opportunities. A graphical overview on the structure of this report is provided in Figure 1.

FIGURE 1 **OVERVIEW ON THE STRUCTURE OF THIS REPORT**



2

OVERVIEW ON THE STATUS QUO

Drainage systems in use today are diverse and differ in the fundamental drainage concept, system layout and mode of transport. Drainage concept hereby refers to the way different streams are dealt with (e.g., separate or combined collection). System layout refers to the technical details of a specific drainage concept (e.g., dimension and layout of pipes). Mode of transport refers to the forces applied to transport wastewater through a drainage network (e.g., gravity, vacuum, pressure). The aim of this chapter is to provide a brief overview on drainage concepts and modes of transport currently in use in the Netherlands from a general perspective. Furthermore, the limitations of each mode of transport with regard to the transport of black water will be exposed.

2.1. DRAINAGE CONCEPTS

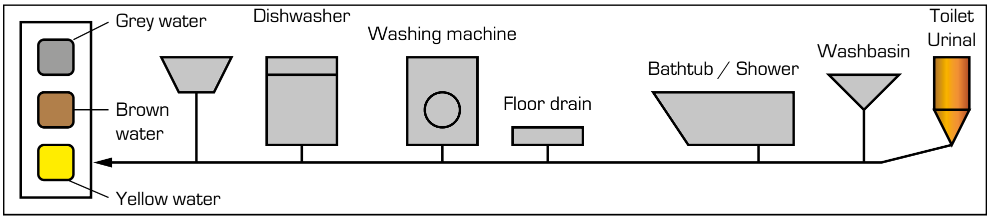
2.1.1. DRAINAGE CONCEPTS INSIDE BUILDINGS

Drainage systems inside buildings normally consist of the part of the drainage network situated between sanitary appliances and house connection (further transport by gravity sewers) or collection tank (further transport by mechanical sewers), respectively. The main differences are to be found in the combination or separation of single streams making up domestic wastewater (i.e., yellow, brown and grey water). The use of kitchen macerators is currently not allowed in the Netherlands (NEN 3215:2007) but green water streams can potentially be combined with either brown or black water streams as indicated by dashed lines in Figure 3 and Figure 4.

Rainwater may in any case only be combined with domestic wastewater streams outside buildings. Generally speaking, three main drainage layouts inside buildings are conceivable: combined collection, partial source-separation, and comprehensive source-separation.

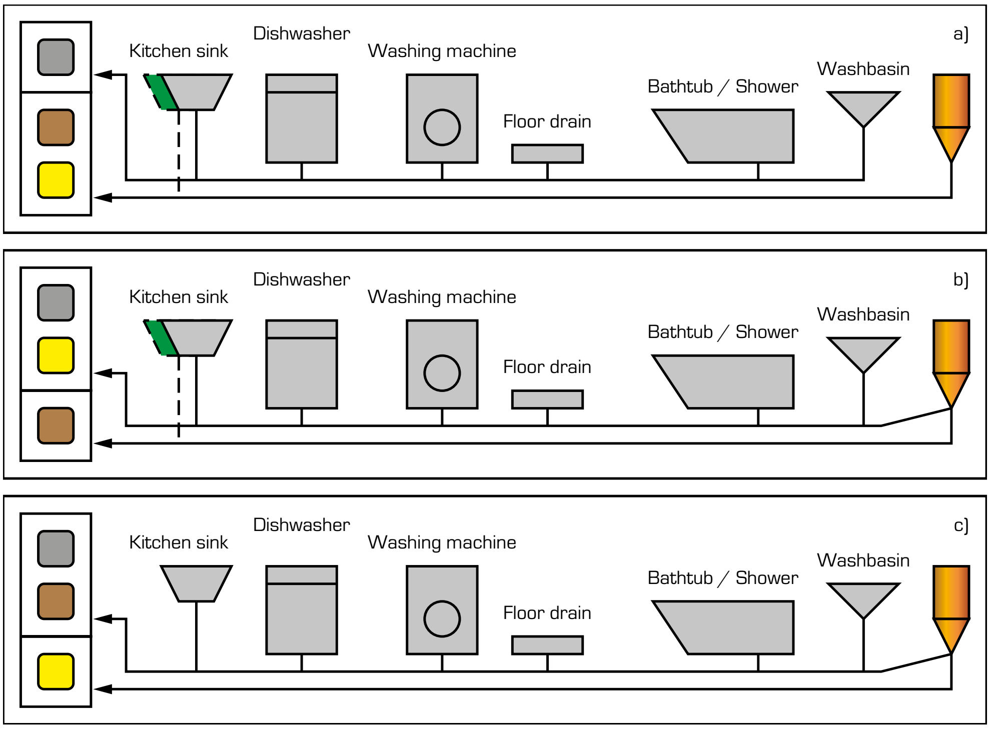
Combined collection (Figure 2) is commonly used in the Netherlands and several other European countries. France in contrast requires a separate collection of black water and grey water inside buildings (Figure 3a). Two other flavours of partial source-separation are separate collection of brown water (Figure 3b) and separate collection of yellow water (Figure 3c). Comprehensive source-separation (Figure 4) is characterised by the separate collection of all types of domestic wastewater.

FIGURE 2 **COMBINED COLLECTION**



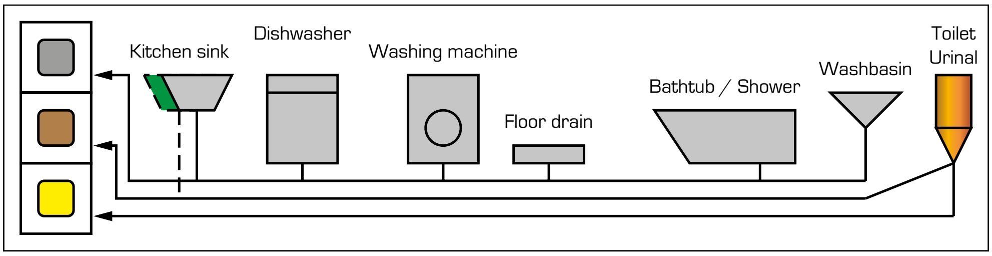
In combined collection concepts, all streams are collected in one common drainage system.

FIGURE 3 **PARTIAL SOURCE-SEPARATION**



In partial source-separation, any of the three main streams making up domestic wastewater is collected separately. a) Separate collection of grey water (or black water) is characterised by a full separation of toilet water from the remaining domestic wastewater. b) Separation of faeces is applied in the context of dry composting toilets in order to reduce the moisture content in the composting compartment. c) Separation of urine has been comprehensively investigated by EAWAG (No-Mix).

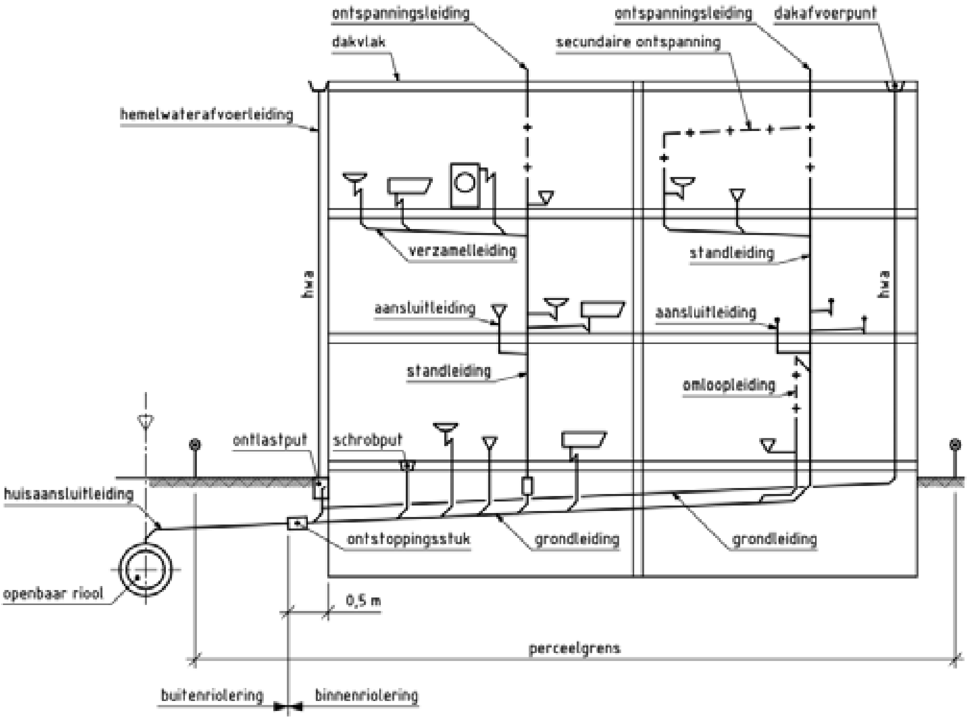
FIGURE 4 **COMPREHENSIVE SOURCE-SEPARATION**



Comprehensive characterisation is similar to separate collection of black water in that toilet water is fully separated from all remaining domestic wastewater streams. Black water, however, is further separated into the yellow and the brown fraction.

The most common drainage system inside buildings in use in the Netherlands is a primary ventilated single discharge stack gravity system according to the Dutch Standard NEN 3215 (Figure 5). This system consists of a drain (grondleiding), a stack (standleiding), several branch discharge pipes (verzamelleidingen) as well as pipes connecting the different appliances to the branch discharge pipe or stack (aansluitleidingen). Furthermore, it is required that the stack features a stack vent (ontspanningsleiding) connecting to the open air outside the building. An exemplary detail drawing is provided in Appendix B.

FIGURE 5 **SCHEMATIC DRAWING OF A COLLECTION SYSTEM INSIDE BUILDINGS (SOURCE: NEN 3215:2007)**

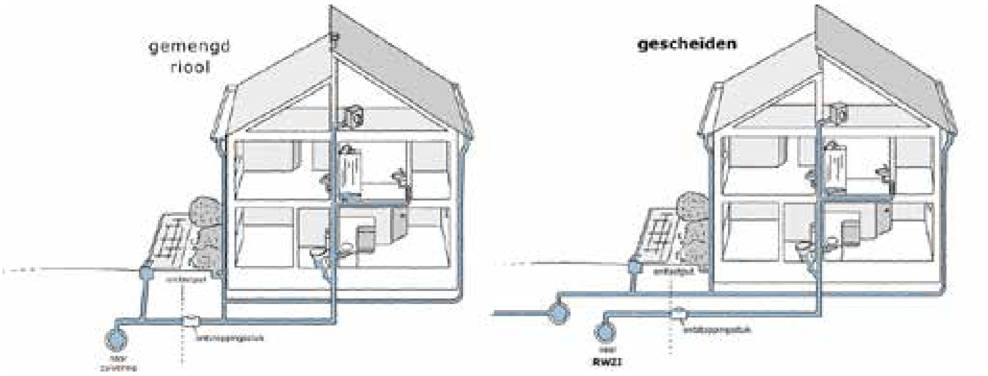


Typically, pipes connecting appliances to the branch discharge pipe or stack should not exceed a length of 3.5 m and are limited to a maximum length of 12 m. Branch discharge pipes to which only a water closet is connected should also not exceed a length of 12 m. Furthermore, the gradient of branch discharged pipes and drains should range from a minimum of 1:200 to a maximum of 1:50. Typical nominal diameters of branch discharge pipes, stacks and drains range from 80 to 100 mm (NEN 3215:2007).

2.1.2. DRAINAGE CONCEPTS OUTSIDE BUILDINGS

Once domestic wastewater has reached the house connection or collection tank, further transport towards the treatment facility needs to be guaranteed. In case of combined collection inside buildings, common drainage concepts outside buildings are combined sewer systems and separate sewer systems. The former are characterised by mixing of domestic wastewater with storm water, whereas the latter keep domestic wastewater and storm water separate (Figure 6).

FIGURE 6 DRAINAGE CONCEPTS OUTSIDE BUILDINGS BASED ON COMBINED COLLECTION INSIDE BUILDINGS (SOURCE: STICHTING RIONED)



In case of partial or comprehensive source-separation inside buildings, a considerable number of other drainage concepts are possible. These concepts are mainly different combinations of local treatment of some streams, and further transport of other streams. Detailed discussion of all possible drainage concepts goes beyond the scope of this report but some scenarios will be discussed in Chapter 3.

2.2. MODES OF TRANSPORT

Irrespective of the drainage concept, the transport of wastewater needs to be brought about by a specific driving force. The three main modes of piped transport currently in use in the Netherlands are transport by gravity, transport in vacuum systems and transport in pressure systems. Most drainage systems inside existing buildings are gravity systems, but vacuum drainage of black water is increasingly being considered in building projects where water savings and source-separation play an important role. Most municipal collection systems outside buildings are either combined or separate gravity sewer systems. In specific situations, gravity sewers are substituted or complemented by vacuum sewers or pressure sewers.

2.2.1. GRAVITY SYSTEMS

Gravity sewers have the advantage that no energy input is required for the actual transport of wastewater as long as no additional pumping is required. Dimensioning of gravity sewers is based on both aspects of hydraulic and self-cleaning capacity. Typical diameters of gravity sewers outside buildings range from 250 to 1500 mm. The European Standard prEN 752.8:2007 states that for small diameter drains and sewers (less than DN 300) self-cleansing (for fine granular sediments, i.e., sand) can generally be achieved by ensuring either that a velocity of 0,7 m/s occurs daily, or that a gradient of at least 1:DN is specified[2].

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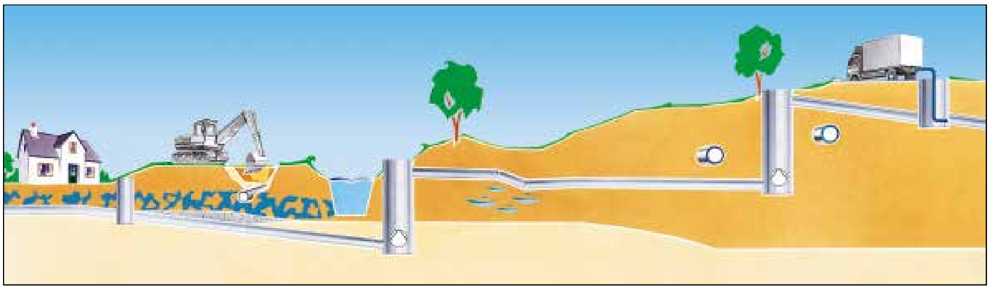
[2] This rule of thumb reflects a minimum shear stress of 2,5 N/m2 and can be obtained by using the formula $\tau = \rho g R S0$, where τ [N/m2] is the shear stress, ρ [kg/m3] the density of water (1000 kg/m3), g [m/s2] is the gravitational acceleration (approximated as 10 m/s2), R [m] the hydraulic radius (R = D/4, where D [m] is the pipe diameter, approximated as D = DN, the nominal diameter), and S0 [-] is the slope of the pipe.

Module B2100 of the Dutch Leidraad Riolering specifies following slopes: between 1:250 and 1:350 for pipes located at the beginning of a branch; between 1:500 and 1:1000 for pipes located further down in the sewer network; maximum 1:100 in areas with sloped terrain. In flat areas, this leads to maximum transport distances of 2-3 km without the installation of pumping stations. Crossing of obstacles or upward sloping terrains, however, requires additional pumping stations (Figure 7).

FIGURE 7 SCHEMATIC DRAWING OF A GRAVITY SEWER (SOURCE: ROEDIGER VAKUUM GMBH)



Further disadvantages of gravity systems are the extent of construction works required for putting large pipes into the ground, sensitivity towards subsidence and leakage (infiltration and exfiltration), potential formation of hydrogen sulphide and possible accumulation of sediment in the pipes or other parts of the gravity sewer network.

2.2.2. VACUUM SYSTEMS

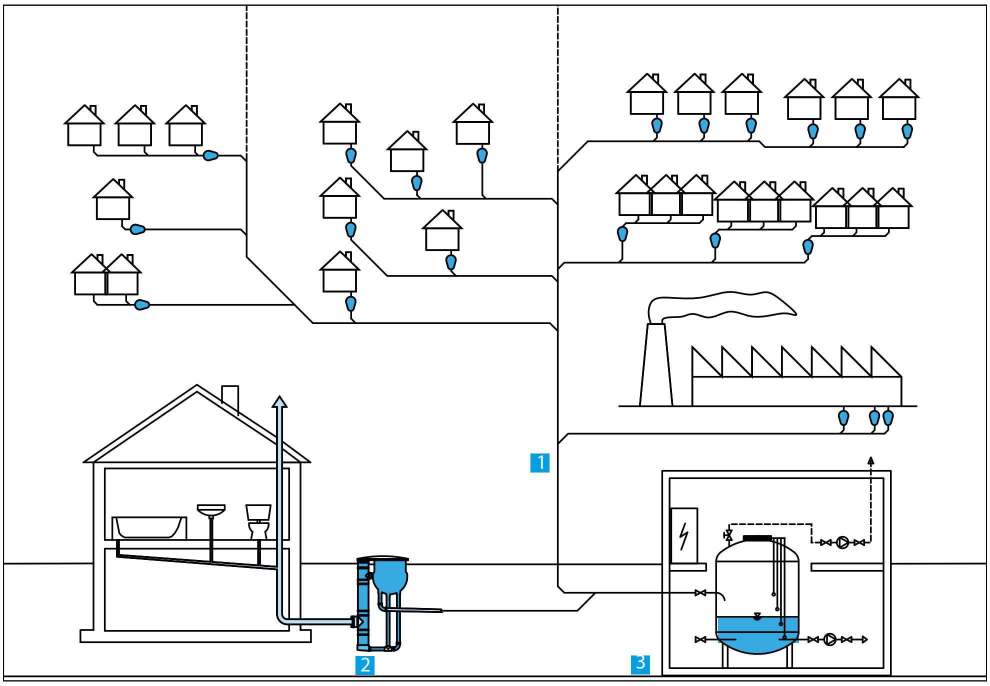
Vacuum sewers for the collection of human excreta were firstly introduced in the second half of the 19th century by the Dutch engineer Liernur (1828-1893). The Liernur system can be considered as a combined solution for both the drainage inside and outside buildings. By the end of the 19th century, Liernur systems were installed in several European cities. However, the system became uneconomic in the early 20th century due to the advent of mineral fertiliser on the one hand and the dilution of excreta by flushing water on the other hand. Furthermore, technical failures and changed philosophies about total sewage collection have contributed to the fact that, to date, none of the Liernur vacuum sewage systems are in operation.

Current vacuum technology is based on a design drafted in the 1950s by Swedish engineer Joel Liljendahl. It has great equality with the Liernur system, but the technological development of one hundred years contributed to a more viable solution. The Liljendahl system allows for different network configurations and network sizes. Its first applications were vacuum toilets for recreational estates and ships, which were later on also used in airplanes and trains. Such vacuum systems normally consist of vacuum toilets, pipework and a vacuum station. Moreover, vacuum systems also allow collection of grey water from shower sinks, washbasins, bath tubes, washing machines, dishwashers and kitchen sinks. In this case, automatic interface units are required, to which water is transported from the sanitary appliances by gravity. Once a certain volume is reached, the collection chamber is automatically evacuated towards the vacuum system.

Vacuum systems allow for both combined and separate collection of grey and black water. In case of separate collection of black water, grey water can be drained using a second vacuum drainage system or by conventional gravity drainage. Typical diameters are on the order of 40 mm for vacuum service lines, 50 mm for vacuum collection lines and 70 mm for main collection lines. The vacuum pump can be located within a building complex or can serve several buildings and be located at a central location in the neighbourhood to be served.

Vacuum drainage systems can also start outside buildings, where collection inside building relies on gravity drainage. These systems are typically referred to as vacuum sewers and consist of several collection chambers, pipework and a central vacuum station (Figure 8), from where the wastewater is pumped towards either a wastewater treatment plant or a conventional gravity sewer. Vacuum systems enable uphill transport (Figure 9 and Figure 10) up to height differences of 8-9 meters (including dynamic head loss).

FIGURE 8 SCHEMATIC DRAWING OF A VACUUM SEWER NETWORK STARTING OUTSIDE BUILDINGS (SOURCE: ROEDIGER VAKUUM GMBH)



IGURE 9 SCHEMATIC DRAWING OF A VACUUM SEWER (SOURCE: ROEDIGER VAKUUM GMBH

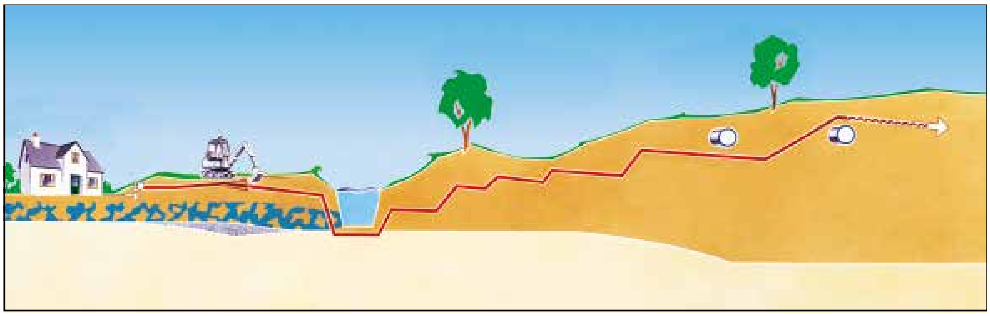
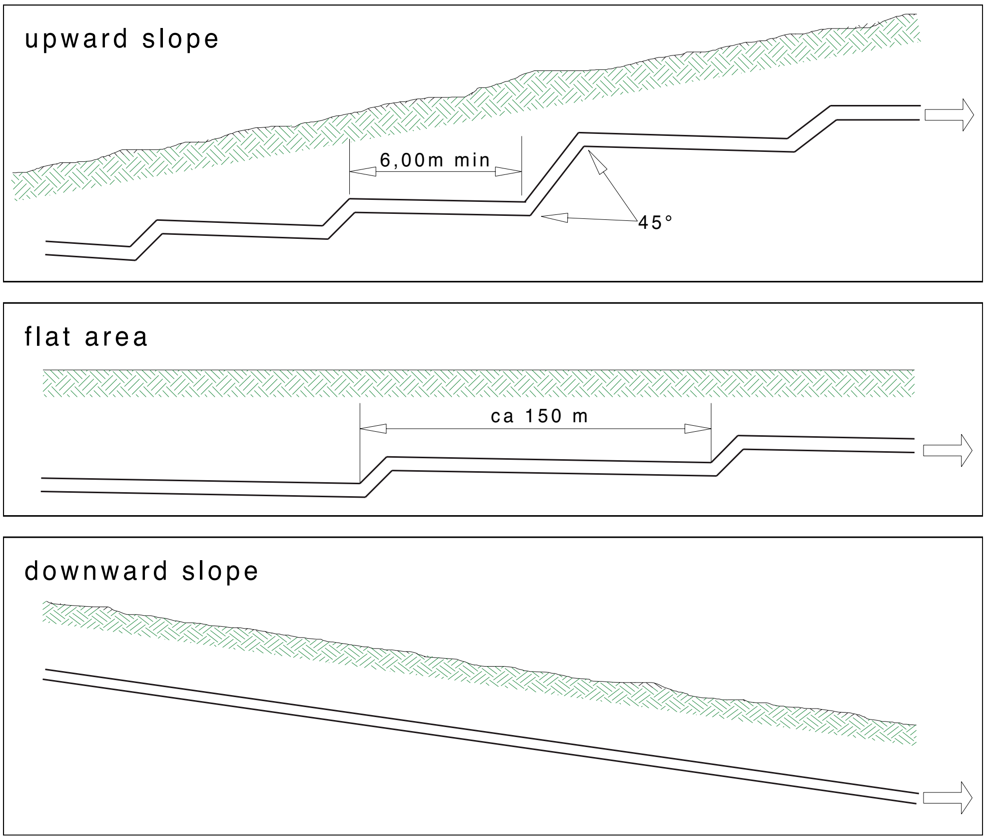


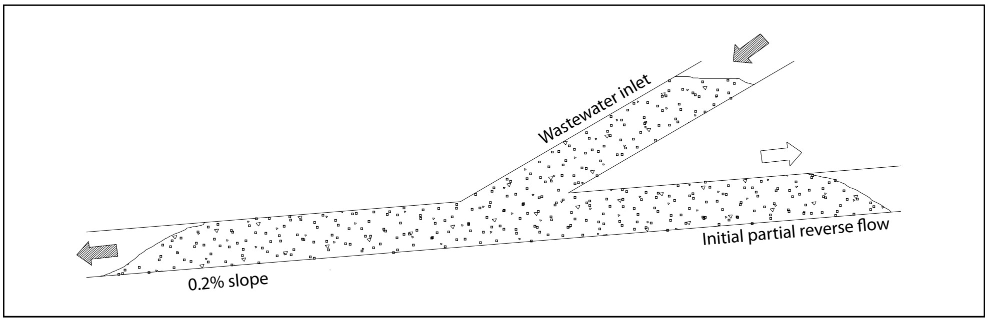
FIGURE 10 VACUUM SEWER SYSTEM PIPE LAYOUT DEPENDING ON TERRAIN SLOPE (SOURCE: VAB ANLAGENBAU)



In flat areas, maximum vacuum sewer branch lengths achievable without additional air intake facilities are roughly 6 km. In this case, distances between subsequent pipe steps are about 150 m leading to a total of 40 steps.

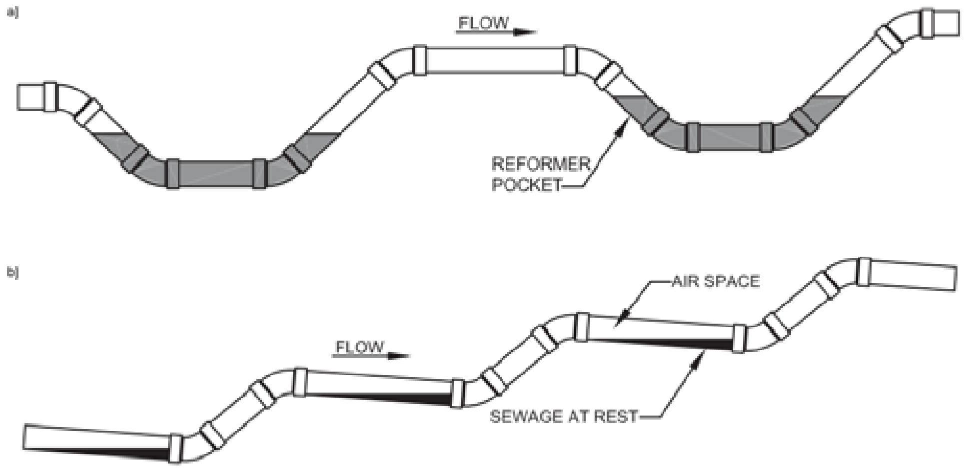
Transport of wastewater in vacuum systems is brought about by the differential pressure between vacuum sewer and atmosphere. Once the valve opens, wastewater is forced from the collection chamber into the sewer main, where about 80% flow in direction of the vacuum station, whereas the rest initially flows into the opposite direction (Figure 11). The direction of flow is then reversed due to the pipe gradient.

FIGURE 11 FLOW PATTERN UPON ADMISSION OF WASTEWATER TO THE VACUUM SEWER (SOURCE: VAB ANLAGENBAU GMBH)



The exact principles of operation of a vacuum sewer system are somewhat empirical. The early concept of liquid plug-flow assumed that a wastewater plug is moved through the pipe due to the differential pressure behind and in front of the plug. Pipe friction would cause the plug to disintegrate, thus eliminating the driving force. Reformer pockets were therefore located in the vacuum sewer to allow the plug to reform by gravity and thus restore the pressure differential (Figure 12a). The current saw tooth profile design concept, however, avoids the formation of wastewater plugs. Air flows above the liquid, thus maintaining a vacuum condition throughout the length of the pipeline (Figure 12b). The liquid is assumed to take the form of a spiral, rotating, hollow cylinder when moving along the pipe propelled by the momentum of the wastewater and the air over the downstream saw tooth lifts until frictional and gravitational forces eventually bring it to rest in another of the lower sections of the saw tooth profile. Both of the above design concepts are approximations and oversimplifications of a complex, multi-phase flow system (WEF, 2008).

FIGURE 12 **TRANSPORT OF WASTEWATER IN VACUUM SEWER PIPES (SOURCE: AIRVAC)**



According to the European Standard EN 1091:1996, vacuum sewers should be given consideration in one or more of the following circumstances: (1) insufficient natural slope (i.e., in flat countryside or to serve low-lying communities), (2) isolated, low- density communities, (3) poor subsoil (e.g., high groundwater water table, unstable soil or rock condition), (4) obstacles to the sewer route (e.g., utility services, waterways), (5) in aquifer protection zones, (6) where there are only seasonal flows (e.g., in holiday resorts), and (7) where it is necessary to minimise the impact of construction work. Power consumption typically ranges from 0.2 to 1 kWh/m^3 of sewage (NEN-EN 1091:1996)[3].

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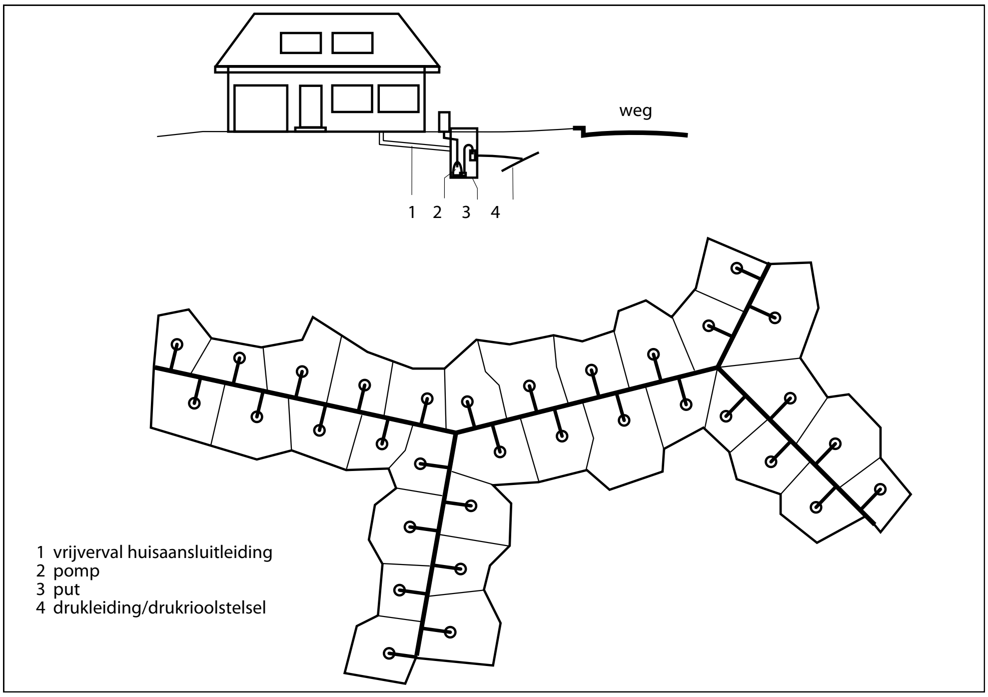
[3] The municipality of Wijchen operates a vacuum sewer with a length of 16.1 km serving 150 collection chambers and reports yearly electricity costs of €6420 (Gemeente Wijchen, Rioleringsbeheerplan 2006-2010). Assuming 2.3 persons per household (collection chamber), each producing 150 l/day of wastewater, and an electricity price of 0.2 €/kWh, energy consumption yields 1.7 kWh/m3.

2.2.3. PRESSURE SYSTEMS

Pressure collection inside buildings is mostly encountered when single sanitary appliances lie below flood level or even below the main sewer line. In these situations, pumps are used to pump wastewater into either the collection system inside the building or directly into the main sewer line. Pressure systems starting outside buildings consist of a collecting tank, a pump and the pipes required to feed wastewater into the sewer main. Grinder pumps effectively reduce solids to slurry. Several tanks and pumps, or pump stations, and pipes form a pressure sewage network (Figure 13). Additional pumping stations are required if branch lengths of about 3 km are exceeded (Vaes et al., 2004).

FIGURE 13 **SCHEMATIC DRAWING OF A PRESSURE SEWER NETWORK (SOURCE: LEIDRAAD RIOLERING, MODULE C3100)**



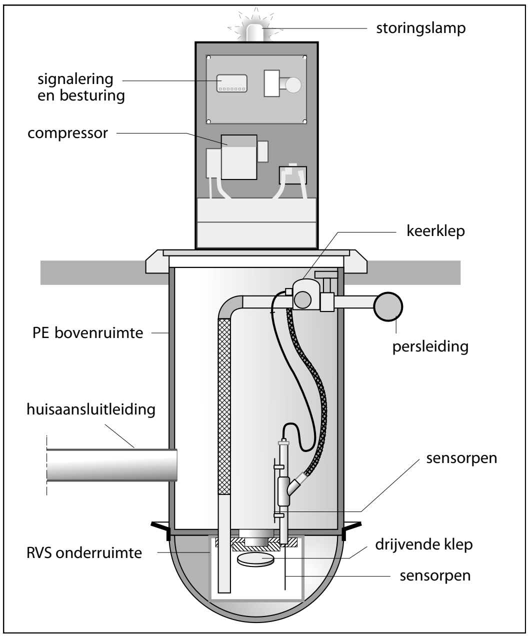
According to the European Standard EN 1671:1997 (CEN, 1997), consideration should be given to pressure sewer systems where one or more of the following apply: (1) insufficient terrain gradient, (2) high ground water levels, (3) low population density, (4) adverse subsurface conditions, (5) when wastewater occurs intermittently (e.g. at camping sites), (6) when the environmental considerations are critical, (7) large scale carriageway repair costs or similar are involved, (8) where there is a proliferation of existing utility services. In the Netherlands, however, pressure systems are mainly applied due to the flat terrain and the resulting limitations to transport by gravity. Power consumption is lower than with vacuum transport[4].

[4] The municipality of Wijchen operates a pressure sewer with a length of 82.8 km serving 556 collection chambers and reports yearly electricity costs of €14223 (Gemeente Wijchen, Rioleringsbeheerplan 2006-2010). Assuming 2.3 persons per collection chamber, each producing 150 l/day of wastewater, and an electricity price of 0.2 €/kWh, energy consumption yields 1 kWh/m3.

2.2.4. PNEUMATIC SYSTEMS

Pneumatic systems (luchtpersriolering) are an alternative to pressure systems. Domestic wastewater is collected in a collection tank and, upon a certain degree of filling, a compressor is started and the wastewater is pushed into the main sewer line. The main advantage of pneumatic systems is that no electromechanic equipment needs to be installed in the collection tank (Figure 14). Furthermore, the formation of hydrogen sulphide is reduced because oxygen is supplied to the sewer system, thereby limiting anaerobic zones. A key difference is that solids are not reduced to slurry. Pneumatic systems can be combined with pressure systems to form hybrid systems.

FIGURE 14 SCHEMATIC DRAWING OF A PNEUMATIC SYSTEM (SOURCE: LEIDRAAD RIOLERING, MODULE C3100)



2.2.5. NON-PIPED SYSTEMS

The main method of transport that does not rely on piped systems is transport by means of lorries. Transport by lorries is applied in the current wastewater infrastructure mainly for the transport of sludge. One the one hand, sludge needs to be removed regularly from septic tanks and small sewage treatment plants serving remote areas. On the other hand, residual sludge from centralised wastewater treatment plants needs to be transported to incineration or composting facilities.

2.3. LIMITATIONS WITH REGARD TO THE TRANSPORT OF BLACK WATER

The key differences between transport of municipal wastewater in combined sewers and black water in separate sewers are the amount of water available as transport medium and flow conditions in the sewer system on the one hand, and the type, distribution and amount of solids carried with the respective wastewater stream on the other hand. Ashley et al. (2004) provide a comprehensive overview on solids in sewers.

Solids found in domestic wastewater only represent a part of the range of solids found in combined sewers and can be broadly divided into fine solids (i.e., fine faecal and other organic particles) and gross solids (i.e., large faecal and other organic matter, paper, rags and miscellaneous sewage litter). Gross solids in sewers may be defined as solids with a specific gravity between 0.9 and 1.2, which can be captured by a 6 mm mesh screen, and which are large enough to be perceived as individual solids. Finer suspended solids in contrast are perceived as general turbidity (Butler et al., 2003).

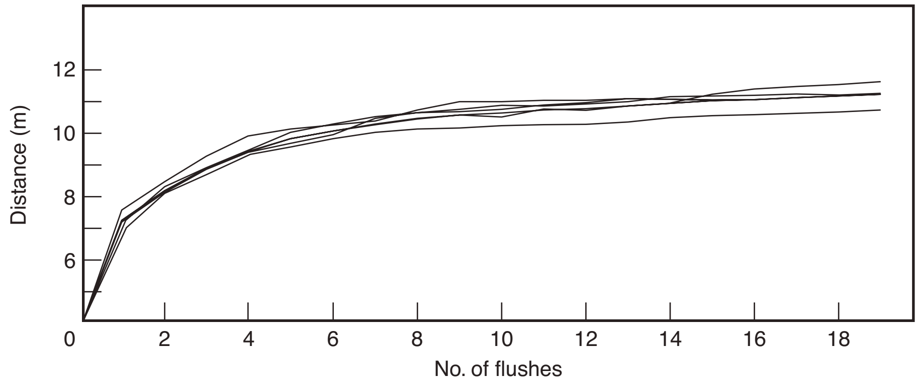
2.3.1. GRAVITY SEWERS

Over the past 20 years, several studies have been carried out in order to understand mechanisms of in-sewer solid movement, and to develop models to predict solid transport in sewer systems. With regard to solid transport, it is important to distinguish between solid transport in intermittent flow and solid transport in continuous flow. Although, strictly speaking, all sewer flows are intermittent flow shall refer to the hydraulic regime in pipes further up in the sewer system, which is characterised by a series of intermittent pulses of flow that attenuate as they translate along the pipe. These flows originate from domestic appliances used throughout the day and, upon combination with other flows, eventually form a quasi-steady flow in larger pipes lower down the system. The latter is also referred to as continuous flow.

SOLID TRANSPORT IN INTERMITTENT FLOW

Littlewood and Butler (2003) have discerned three different transport mechanisms for intermittent flow conditions in small sewer pipes (< 150 mm) and coined the term 'sliding, leaking dam' mechanism for what they found the most usual transport mechanism. In this mode of transport, solids introduced via the WC (faecal stool, toilet paper, sanitary products) are propelled along the pipe invert due to the build up of head behind the solid. Whether the solid moves is dictated by a combination of friction effects and forces on the back of the solid. The experiments conducted by Littlewood and Butler revealed a 'limiting solid transport distance' that depends on pipe diameter, type of solid and flush characteristics (Figure 15). The first flush moves the solid the greatest distance, while subsequent flushes move it decreasing distances.

FIGURE 15 LIMITING SOLID TRANSPORT DISTANCE (SOURCE: LITTLEWOOD AND BUTLER, 2003)



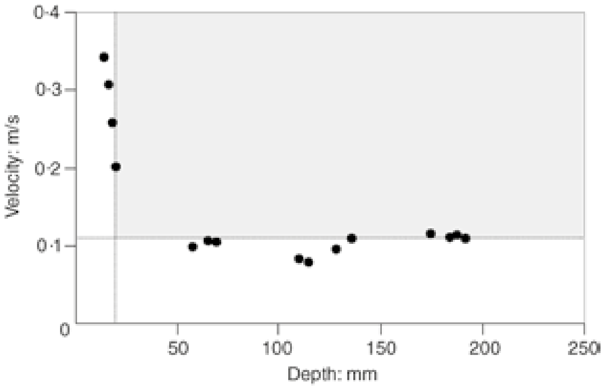
McDougall and Wakelin (2007) further investigated the influence of flush volume and branch drain cross-section on deformable solid transport in attenuating flows. Based on these papers it seems adequate to assume a limiting solid transport distance between 10 and 20 m in small sewer pipes subject to intermittent flow.

The application of flush enhancers might intuitively be seen as a possibility to overcome above transport limitations. The effect of flush enhancers is a reduction of the number of flush waves with a concurrent increase of the flush volume. Accordingly, limiting solid transport distances for larger flush volumes can be taken as rough indication of the potential effect of flush enhancers on solid transport. Overall, no substantial increase in the limiting solid transport distance is expected since the general flow pattern is still intermittent in nature.

SOLID TRANSPORT IN QUASI-STEADY FLOW

Under quasi-steady flow conditions, solids are transported with the flow in a process normally referred to as 'advection'. Transport by advection requires a certain minimum flow velocity (shear stress) and a certain minimum water depth. These minimum requirements depend on the type and the characteristics of the solids. If either requirement is not satisfied, the respective solid type is deposited (Butler et al.,
2003). Figure 16 shows these minimum requirements for sanitary towels.

FIGURE 16 **MINIMUM REQUIREMENTS FOR ADVECTIVE TRANSPORT OF SANITARY TOWELS (BUTLER ET AL., 2003)**



The critical values investigated by Butler et al. (2003) are derived from a laboratory installation using varying combinations of pipe gradient and downstream control level. The set of points close to a vertical line (depth approximately constant) represent deposition conditions for varying pipe gradients with no downstream depth control. The sets of points lying close to a horizontal line (velocity approximately constant) represent various combinations of pipe gradient and setting of downstream depth control. If conditions fall within the shaded part, solids of the type investigated would be assumed to be carried with the flow; within the non-shaded part, deposition would be assumed to occur.

MINIMUM REQUIREMENTS FOR THE TRANSPORT OF LARGE SOLIDS

Transport conditions under intermittent flow are insufficient to transport solids further than the limiting solid transport distance, unless conversion processes take place in the sewer system that degrade large solids into smaller solids that can be transported further under intermittent flow conditions. To guarantee sufficient solid transport over extended distances in black water gravity sewers, certain minimum velocities and minimum water depths are required over a specific period, once the limiting solid transport distance is reached. The exact conditions depend on a number of factors such as pipe diameter, pipe geometry, pipe material, or type of solid.

2.3.2. VACUUM SEWERS

Both collection of black water inside buildings using vacuum toilets and transport of domestic wastewater outside of buildings using vacuum sewers can be regarded as proven technology. Vacuum sewer systems have been used in areas with water conservation measures and appear to perform properly. This is supported by the application of vacuum technology in the cruise ship industry. For many years, cruise ships have successfully used internal vacuum systems, with vacuum toilets that use as little as 0.9 litres of water per flush (WEF, 2008). However, the sum of static and dynamic losses is limited to 8-9 m.

2.3.3. PRESSURE SEWERS

Both pressure toilet units and the transport of domestic wastewater outside of buildings using pressure sewers can be regarded as proven technology. However, design rules and practical experience with such systems might not be applicable to the transport of solely black water outside of buildings. No specific literature was found on the transport of black water in pressure sewers. However, transport of viscous fluids in food or chemical processing industries might give an indication of the feasibility of the transport of black water in pressure sewers.

2.3.4. PNEUMATIC TRANSPORT

Early pneumatic transport systems with a central compressor station suffered from problems regarding reliability and proneness to failure (Leidraad Riolering, Module C3100). Current pneumatic transport systems feature individual compressors for every collection tank and the layout is very similar to pressure sewers. The main difference to pressure sewers, however, is that solids are not reduced to slurry and therefore larger solids may enter the system. The performance of pneumatic sewers for the transport of solely black water is uncertain and no specific literature was found.

2.3.5. NON-PIPED SYSTEMS

The transport of sludge by lorries is common practice in current wastewater management systems. No special restrictions are expected with regard to transport of black water expect for larger volumes in case of usage of conventional water closets.

3

POTENTIAL OF SOURCE-SEPARATION

Existing combined collection of black and grey water inside buildings considerably complicates prompt and comprehensive separate collection of black water in the existing building infrastructure. Furthermore, there are several limitations when it comes to the transport of black water using current modes of transport. This chapter shall outline the potential for separate collection of black water in the existing building infrastructure by means of conventional drainage concepts and modes of transport on the one hand, and ideas based on thinking outside the box on the other hand. The main questions thus are which constituents we want to separate how and where, which constituents can be separated how and where, and how these constituents can be transported towards a treatment facility. Section 3.1 briefly introduces a distinction of building types. Sections 3.2 and 3.3 outline diverse concepts for source-separation and transport of separated streams, respectively, and discuss their applicability to different buildings types. Section 3.4 sheds light on the interrelation between source- separation and transport concepts and provides a summary on the various concepts.

3.1. DISTINCTION AND DISTRIBUTION OF BUILDING TYPES

With respect to discharge patterns and wastewater composition, buildings can be broadly divided into residential buildings, public buildings, commercial buildings, office buildings, and industrial buildings. The four former categories are subject to rather typical discharge patterns and the wastewater composition is similar to domestic wastewater, whereas industrial buildings show large variations depending on the type of industry. In this research, only residential, public, commercial, and office buildings are considered.

TYPES AND DISTRIBUTION OF RESIDENTIAL BUILDINGS

Residential buildings can be further divided into ground floor housing and apartment complexes given the differences in the amount of appliances connected to the stacks and drains. In the Netherlands, on average 69% of the dwellings are ground floor housings (eengezinswoningen). Only the provinces of Noord-Holland (54%) and Zuid- Holland (52%) range below this average due to the cities of Amsterdam (15%), Den Haag (22%) and Rotterdam (27%). A graphical overview on the percentage of ground floor housing in various COROP[5] regions of the Netherlands is provided in Figure 17.

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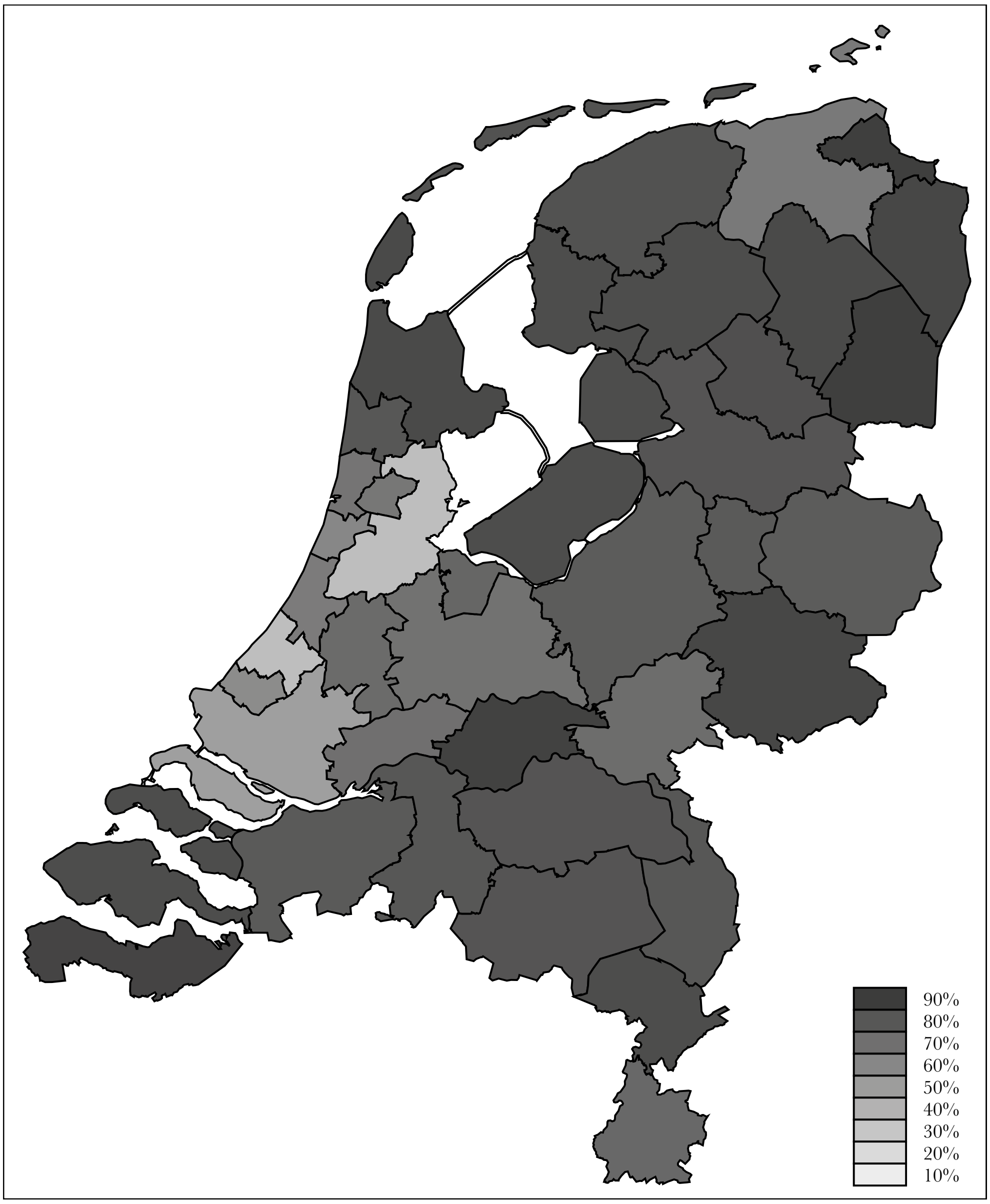
[5] COROP (Coördinatie Commissie Regionaal Onderzoeks Programma) regions are regions in the Netherlands used for statistical purposes.

FIGURE 17 PERCENTAGE OF GROUND FLOOR HOUSING IN DIFFERENT COROP REGIONS OF THE NETHERLANDS



With respect to the potential for source-separation in residential buildings, it is important to realise that regional differences (i.e., presence or absence of crawl spaces, length of renovation cycles, percentage of owner-occupied and rented accommodation) may have a considerable impact on the feasibility of specific source- separation concepts. The extent of these regional differences, however, will not be investigated further. The focus of this chapter is clearly on drafting diverse ideas on how separation and transport can be achieved in general rather than on regional peculiarities. Thereby, differences between residential buildings and office-type buildings will be taken into account.

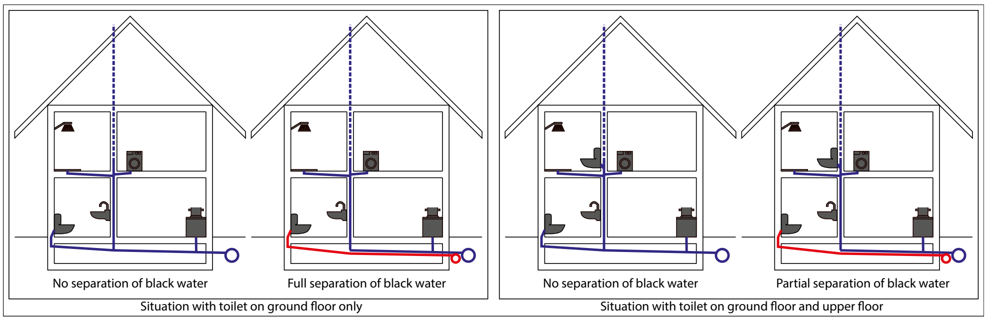
3.2. SOURCE-SEPARATION IN EXISTING BUILDINGS

Generally speaking, separation of streams can be either spatial or temporal or a combination thereof, and initial separation can take place inside or outside buildings. In this paragraph, several modifications to the existing drainage systems are discussed that aim at facilitating the separate collection of black water or constituents thereof. The main guiding principle was to look for concepts with minimal structural changes to existing buildings.

3.2.1. MODIFICATIONS IN THE CRAWL SPACE

This scenario only applies to ground floor housing where toilets are located on the ground floor and connect to the stack or drain only in the crawl space. This context offers the possibility of a relatively easy disconnection of this particular toilet from the combined system and reconnection to a new separate system. If additional toilets are located on higher floors, separate collection of black water is only partially possible if no additional source separation measures are implemented (Figure 18).

FIGURE 18 DISCONNECTION AND RECONNECTION OF TOILETS LOCATED ON THE GROUND FLOOR



Knowing that 69% of the Dutch dwellings are ground floor houses, it seems that there is a considerable potential for separate collection of black water by this means. But it is uncertain how many of the ground-floor houses feature toilets on the upper floors, and which fraction of the black water originates from these upper floor toilets. Furthermore, it is uncertain how many of the ground floor toilets can be easily disconnected from the combined system and reconnected to a separate system. This depends on the sewer layout within the building.

At a very rough estimate, it is possible to collect on average 35% of the black water originating from domestic toilets in the Western part of the Netherlands (Randstad) and 50% in the rest of the country using this concept. This rough guess is based on following assumptions: half of the houses only feature one toilet in the ground floor; in the remaining half of the houses, 60% of the black water originates from toilets located on the ground floor; roughly 10%-15% of the Dutch houses do not feature a crawl space. Regional differences, however, will be considerable.

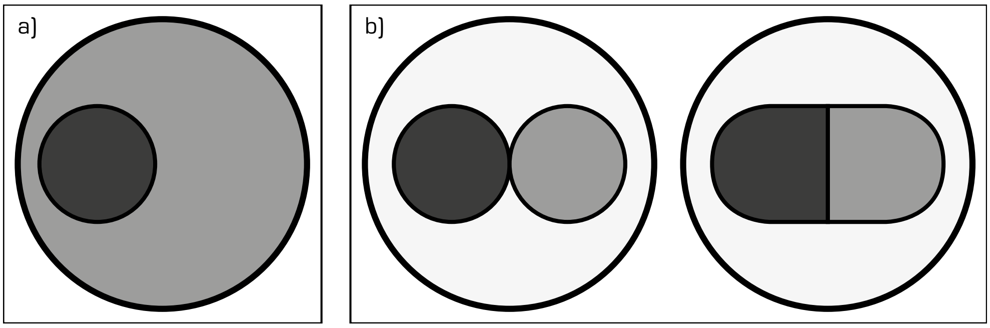
3.2.2. PIPE WITHIN PIPE

The core of this scenario is the introduction of a small-diameter flexible pipe into the existing drainage network (Figure 19a). Key advantage of this approach is the perspective of a complete and comprehensive physical separation of black and grey water already at the level of every single sanitary appliance. Albeit seemingly intuitive, there are several technical difficulties related to this approach.

First of all, the inner drainage system must enter the outer drainage system at some point and must leave it at some other point. Whereas entering the outer pipe at the sanitary appliance to be reconnected is relatively straightforward, leaving the outer pipe is more complicated. Either an opening must be made in the existing outer pipe or a section of it must be replaced. If more than one sanitary appliance is connected to the new system, junctions are required in addition. These are difficult to realise since located inside the existing drainage system. Furthermore, these junctions need to be absolutely tight to prevent leakage and should not obstruct the flow in the outer pipe. Even if realisation of junctions were successful, there is a serious risk of gradual build- up of blockages in the outer pipe ahead of pipe bends, junctions of the inner pipe and the location where the inner pipe leaves the outer pipe. Removal of such blockages might cause damage to the inner piping.

Junctions can be avoided if only one sanitary appliance is connected to the interior drainage system, for instance the toilet in the upper floor. But this does not fully eliminate the risk of blockages. Alternatively, a twin pipe (Figure 19b) can be introduced into the existing drainage system instead of a single pipe. This has the advantage of preventing blockages in the outer pipe caused by the inner pipe. Junctions however become more complicated since a twin junction needs to be established inside of every existing junction.

FIGURE 19 SCHEMATIC DRAWING OF THE PIPE WITHIN PIPE CONCEPT



Apart from uncertainties with regard to its feasibility, the main drawback of the pipe within pipe concept is related to the mode of transport applicable in small-diameter flexible pipes: vacuum transport. Depending on a single or twin pipe approach, this requires the installation of vacuum toilets and/or automatic interface units6.

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6 There might be a chance, however, to keep conventional water closets and add an automatic interface unit between water closet and vacuum drain.

3.2.3. RETROFIT OF DUAL PIPE DRAINAGE SYSTEM

Comprehensive retrofit refers to a concept where a single building or a group of buildings is renovated or reconstructed. Such renovation or reconstruction works provide an excellent opportunity to establish full source separation on the level of a whole building or even neighbourhood. The new dual drainage system of course needs to take into account the space provided by the existing structure of the building. The two main conventional modes of transport suitable to this concept are gravity collection and vacuum collection. It is worthwhile to note that in some specific contexts (i.e., when two stacks are present in a specific building, one serving the kitchens, the other serving the bathrooms) it might be possible to establish a dual pipe system by simply reconnecting grey water sanitary appliances to the kitchen stack, leaving only toilets connected to the bathroom stack. Yet the hydraulic conditions in the kitchen stack must be investigated, especially in view of minimum diameters for the connection of bathtubs.

3.2.4. SMART HOUSE CONNECTION

The core of this concept is a smart house connection that aims at diverting black water and grey water into two different pipes or collection tanks, thereby taking advantage of sequential usage of sanitary appliances. A successful implementation requires that two basic conditions be met. First, the percentage of toilet flushes without concurrent usage of a second sanitary appliance must be high. Second, the house connection must know what is black water and what is grey water in order to divert it accordingly. With regard to stream diversions, two general scenarios are thinkable: toilets that communicate the incident of a flush to the house connection, or house connections that can sense themselves whether black or grey water is flowing through. Possible parameters that can be used to achieve the latter include salinity, nitrogen concentration, pH, presence of large solids, and temperature. Alternatively a tracer can be added to the flush water. Regardless of the parameter used, sensors must be robust and reliable, able to respond quickly to changes in the parameter value, and should not obstruct the flow. The main advantage of this concept is that no changes are necessary inside the building, but this advantage comes at the price of several downsides. First of all, concurrent usage of toilets and other sanitary appliances can lead to a mixing of streams before separation can take place. Furthermore, nonuniform transport of the liquid and solid fraction of black water may also lead to a partial mixing of streams before arrival at the house connection. Whereas the liquid fraction travels from the toilet towards the house connection without interruption, the solid fraction will likely be deposited on the way and is transported with the next discharge wave(s), irrespective of their origin. As a result, a number of undesired separation scenarios are possible: diversion of diluted yellow water into the grey water collector, diversion of gross solids transported by grey water into the grey water collector, and undesired dilution of the fraction diverted into the black water collector. A proper design of the house connection thus is key to a successful implementation of the concept. Yet the concept is prone to cross contamination between streams.

CONCURRENT USAGE OF TOILETS AND OTHER SANITARY APPLIANCES

Whether or not it is sensible to apply the smart house connection concept in a specific context first and foremost depends on the amount of black water that can be collected separately. It is estimated that the smart house connection concept is suitable in case no more than approximately five apartments are connected to the same smart house connection. More details on this estimation are presented in Appendix C.

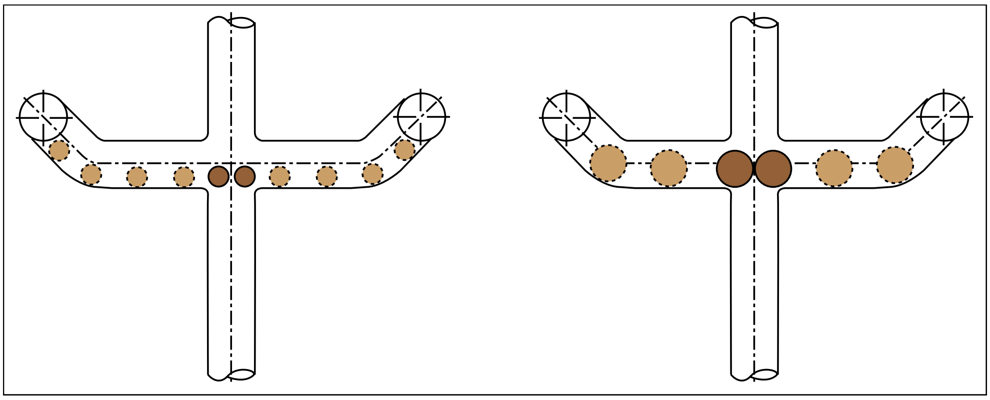
3.2.5. SEALING TOILETS

The sealing toilet concept refers to the application of toilets that seal human excreta into some kind of bag. It is anticipated that the main design challenges are to develop a reliable, robust, safe and easy to use sealing mechanism for the hygienic and hermetic sealing of human excreta, whilst a sufficient level of user friendliness and comfort is provided. The bags thus obtained can be either flushed through the existing drainage system or can be disposed of by an alternative means.

WET SEALING TOILET

In case of disposal via the existing drainage system, spatial separation of black and grey water is accomplished within the existing drainage system without any changes to the system apart from the installation of a new toilet. An advantage is that sewer gas is trapped within the black water bags and cannot escape to the atmosphere or deteriorate the sewer system. To prevent cross contamination, the sealed bags must not leak. Further, they must be transportable through the existing drainage system. To this end, spherical shaped bags with a diameter smaller than half the stack diameter seem most promising. Larger diameters may cause blockages in case of junctions or two branch discharge pipes connected to the stack at the same height (Figure 20). With spherical bags, this risk is likely negligible but it must be ensured that the spherical shape is kept throughout the whole transport trajectory. To ensure a minimum rigidity of the bags, either a naturally rigid shell can be used, or an elastic shell can be applied in combination with excess pressure in the interior of the shell.

FIGURE 20 SCHEMATIC DRAWING OF BAGS WITHIN BUILDING DRAINAGE SYSTEMS AND THE RISK OF BLOCKAGE



Left: Sealing bags smaller than half the stack diameter do not cause blockage in case of concurrent discharge from two branch discharge pipes. Right: Sealing bags larger than half the stack diameter may lead to blockage in case of concurrent discharge from two branch discharge pipes.

Application of spherical bags with a diameter of 45 mm yields transport volumes of 0.05 litres per transport unit, which is clearly insufficient. Increasing the diameter to 70 mm yields a transport volume of 0.18 litres per transport unit, which is still critical for the 'grote boodschap'.

Two solutions are the application of non-spherical bags or the splitting of one toilet flush into multiple bags. The former approach is prone to blockages at pipe bends whereas the latter complicates the design of the sealing toilet. Moreover, sealing toilets may run out of sealing bags. In this case, toilets can be used but excreta will not be removed from the toilet until sealing bags are replenished, and an extended volume needs to be transported once sealing bags are available again. Another disadvantage is that treatment plants need to be upgraded in order to be able to process the black water bags propelled through the sewer with the remaining wastewater. Furthermore, care must be taken that bags do not get damaged under way, for example by pumping stations.

DRY SEALING TOILET

The problem of limited transport volumes faced by water-borne transport of sealing bags can be avoided by choosing an alternative transport route. Disposal of the bags hereby can take place in several ways. A comfortable method is direct disposal by means of a pneumatic transport system (buizenpost). But retrofitting of such systems in existing buildings requires considerable efforts. Existing ventilation pipes might be used for the transport inside buildings, but alternative ventilation is then required. A more straightforward, though less comfortable alternative is disposal of the bags by means of a pneumatic system starting outside buildings. Hereby, synergies may arise for the combined collection of solid waste and human excreta since the same pneumatic collection system can be used for both types of waste. Yet the sealed bags must somehow find their way from the toilet to the point of disposal. Hence comfort might be reduced compared to conventional water closets. Albeit normal practice for solid waste, users might not accept that they will have to bin their excreta with this new concept, instead of using conventional water closets with the convenient flush and forget mentality. Another disadvantage is that upon depletion of sealing bags, the toilet cannot be used at all. The same applies upon failure of the sealing mechanism.

3.2.6. TOILET OUTSIDE THE APARTMENT

A further concept based on source-separation outside of buildings is based on the dislocation of toilets to a place where separate collection can be easily established. In case of ground-floor housing, toilets units could be located in existing garages or barns, or in annexes to the existing buildings. Such toilet units could be planned for a single house or for a number of houses together. In apartment complexes, toilet facilities could be located within the building, for example on every floor. Such toilet facilities could consist of private units only accessible to a certain household, or shared units accessible to a number of households. Albeit compelling on a conceptual level, the toilet outside the home concept suffers from a severe reduction of user comfort.

3.2.7. GREY WATER TO THE STORMWATER DRAIN

In case domestic stormwater drains are connected to combined sewer systems, sanitary appliances discharging grey water might be connected to the stormwater drain for separate collection of grey water and stormwater. This practice, however, renders separate collection of rainwater impossible.

3.3. TRANSPORT OF SEPARATED STREAMS

Once domestic wastewater is separated into a black water and a grey water stream, these streams must be transported further towards a treatment facility. Generally speaking, various wastewater streams can be transported temporally or spatially separated. In this paragraph, several modifications to existing transport systems are discussed that aim at facilitating the separate transport of black water. The main guiding principle was to look for concepts that possibly still make use of the existing urban water infrastructure outside buildings.

3.3.1. SEPARATE BLACK WATER SEWER

The construction of separate black water sewer systems would be the logical extrapolation of the evolution from combined sewer systems to separate sewer systems. There main different possible methods are gravity sewers, vacuum sewers, pressure sewers and effluent sewers in combination with a septic tank.

GRAVITY SEWER

Given that transport of black water in small gravity sewers under intermittent flow is limited to short distances (see paragraph 2.3.1), solid transport thus needs to be enhanced by addition of some transport agent. One possibility is to discharge additional quantities of water through the sewer system to increase the flow. Alternatively, some sort of cleaning mechanism can enforce solid transport.

Vaes et al. (2004) have investigated possibilities to enhance the self-cleaning capacity of foul sewers by means of using rainwater as additional flushing water. Discharges on the order of several litres per second are applied in order to establish sufficient shear forces for the transport of sediments[7]. For a flush of one minute per day, a total volume of several hundred litres would be required based on this approach. Depending on the number of households connected to a certain sewer branch, this can lead to a substantial further dilution of the black water. If intense rainfalls are sparse, large storage tanks must be built locally that are able to supply the water at the desired discharge rate.

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[7] The required discharge is chosen as the capacity of a half-full pipe and depends on the pipe diameter and the slope of the pipe. For a pipe with a diameter of 100 mm and a slope of 8.2‰, the discharge amounts to 2.3 l/s; for a pipe with a diameter of 150 mm and a slope of 5.4‰, the discharge amounts to 5.5 l/s (Vaes et al., 2004).

In analogy to the small-scale closed-cycle system of Boehler et al. (2007), a gravity sewer with water recycling could be considered. The transport liquid does not necessarily need to be water, as long as it can be fully recovered before or during treatment of the black water and does not have adverse effects on the environment in case of pipe leakage or residuals in the effluent of the treatment facility. Upon arrival at the treatment facility, the solid fraction is separated from the liquid fraction. If a flushing liquid different than water is used, the flushing liquid is separated and recirculated to the black water sewer. If water is the flushing liquid, part of the water is recirculated to the black water sewer, whilst excess water originating from flushing the toilets is removed from the flushing cycle and subjected to further treatment.

A different type of measure is represented by some kind of mechanical solid transport enhancement. To this end, plugs could be applied to push solids through the sewer system. These plugs could be either self-propelled or propelled by applying pressure to the sewer system. In the latter case, however, house connections must feature non- return valves that prevent that the elevated pressure propagates into the building drainage system. Moreover, problems might arise if wastewater is unable to leave the building drainage system during the cleaning cycle of the main sewer.

MECHANICAL SEWER SYSTEM

Solid transport can alternatively be effectuated by the application of vacuum, pressure or pneumatic sewers[8]. All implementations based on mechanical sewers are combined with the construction of a collection chamber for black water originating from one or more houses. Source separation concepts can thereby vary from building to building. The collection chamber is emptied intermittently by means of either a vacuum sewer connected to a remote vacuum station or a pump or compressor connected to a pressure sewer network. From the vacuum station or pressure sewer network, black water is sent to the treatment facility, where nutrients and energy are recovered. The residual sludge and the effluent are then transported to the municipal wastewater treatment plant for final treatment, possibly through the municipal sewer system.

EFFLUENT SEWER

This implementation refers to a system where source-separated black water from one or more buildings is discharged to a septic tank where solids are settled and retained until the tank is emptied. Source separation concepts can thereby vary from building to building. Solids are transported intermittently removed and transported to a treatment facility with lorries, whereas the septic tank effluent is transported towards a treatment facility geared towards nutrient recovery using a gravity system with very small pipe diameters. This system needs to be constructed. The treated effluent will be discharged to the municipal sewer for final treatment in the municipal wastewater treatment plant.

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[8] Pneumatic sewer refers to sewers where wastewater is transported without any specific container around it. Transport of human excreta in some kind of container by means of pneumatic systems is referred to as pneumatic transport system or pneumatic waste collection system.

3.3.2. SEWER WITHIN SEWER

Similar to the pipe within pipe approach, it is thinkable to retrofit a small diameter black water pipe into an existing combined or separate sewer system. Connections are more easily done since manholes give sufficient access. In combined sewer systems, gravity black water sewers might be feasible due to the larger diameter of the combined sewer pipes. In separate systems, the black water sewer might be limited to vacuum or pressure systems due to the smaller diameter of foul sewer pipes. In any case, the new pipes must be flexible in order to be introducible through manholes to the existing sewer pipes. The main challenges of this approach will be the proper installation of the new sewer pipe without leading to a grey water system prone to blockage or depositions due to insufficient or unsteady gradients.

3.3.3. RETROFIT OF DUAL PIPE SEWER SYSTEM

Comprehensive replacement works of existing sewers provide an excellent opportunity to establish spatially separated transport systems for grey and black water.

3.3.4. SMART SEWER SYSTEM

Similar to the smart house connection concept, sequential discharge is a possible way to transport black water separate from grey water. Smart sewer system refers to sewers with such sequential transport of separate streams. An added challenge in comparison with smart house connections is that stormwater, drainage water and industrial wastewater might be added to the municipal sewer. The design goal thus must be to retain black water in a storage tank until there is a slot where no rainwater (in case of combined, hybrid and improved separate sewer systems) and no industrial water are discharged to the sewer system. However, influx due to leakage or connection of drainage pipes to the sewer system might still be present.

As in the case of the smart house connection, discharge of black water is likely subject to nonuniform transport of the solid and liquid fraction. Such a scenario would require the building of retention tanks for black water for every single building or group of buildings. The implementation in completely separate sewer systems has the highest chances of success, whereas a successful implementation in combined and hybrid systems appears rather doubtful. In any case, considerable disadvantages of such an approach are the risk of cross-contamination between streams and the problem of nonuniform transport of liquid and solid fractions. Whereas control of this problem seems still feasible on the level of a single building, solutions on the level of a whole sewer network are disproportionally more complex.

3.3.5. SEALING HOUSE CONNECTION

In analogy to the sealing toilet, a concept with a sealing house connection is thinkable. Black water that is separately collected is temporarily stored in a collection tank. Once a certain level is reached, part of the black water is sealed into a bag and discharged to the municipal sewer. The maximum volume of the bags depends on the diameters of the existing sewer pipes and will be considerably larger in case of combined sewer systems than in case of separate sewer systems. As with the sealing toilet concept, the sealing house connection concepts requires upgraded treatment plants that are able to process the black water bags propelled through the sewer with the remaining wastewater, and care must be taken that bags do not get damaged during transport. Alternatively, bags could be discharged to a pneumatic waste collection system.

3.3.6. PNEUMATIC WASTE COLLECTION SYSTEM

Human excreta could also be transported in much the same way as other solid wastes are transported. One method applied in the context of solid waste collection is the installation of a pneumatic waste collection system (Figure 21). In such systems, users throw their waste into readily accessible inlets either indoors or outdoors, where the bags are stored temporarily above a closed storage valve. Full inlets are emptied at regular intervals via a system of underground pipes leading to a collection station building on the periphery of the area served.

FIGURE 21 SCHEMATIC DRAWING OF A PNEUMATIC WASTE COLLECTION SYSTEM (SOURCE: ENVAC GROUP)

Pneumatic waste collection systems are already operative in several European cities and enable the transport of residual waste, organic food waste, mixed recyclables, paper, and cardboard in the same pipe. Addition of a further type of waste might be possible with only minor modifications to the existing system. Collection points can be either inside or outside buildings. How the bags get from toilet to collection point depends on the transport concept inside the respective building.

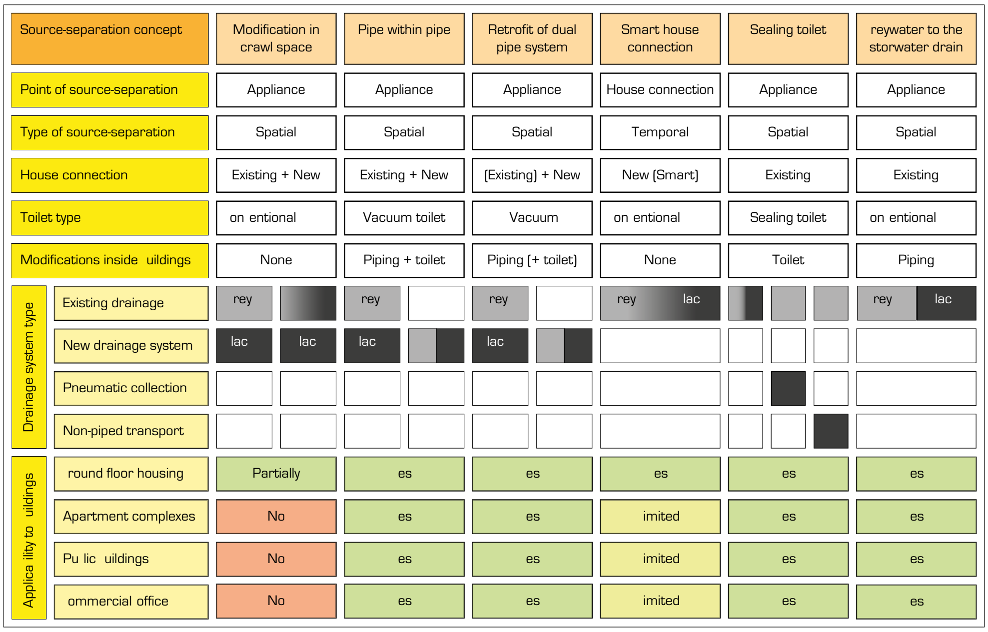
3.3.7. NON-PIPED TRANSPORT

Non-piped alternative modes of transport are mainly transport by lorries. These lorries can be mobile vacuum stations in combination with local pneumatic waste collection systems, tank lorries in combination with local black water collection and storage tanks (possibly retaining only the solid fraction), or conventional waste collection lorries in combination with binned disposal of human excreta.

3.4. SYNTHESIS AND OVERVIEW

The main characteristics of the source-separation and transport concepts and their applicability to different building types are summarised in Figure 22 and Figure 23, respectively.

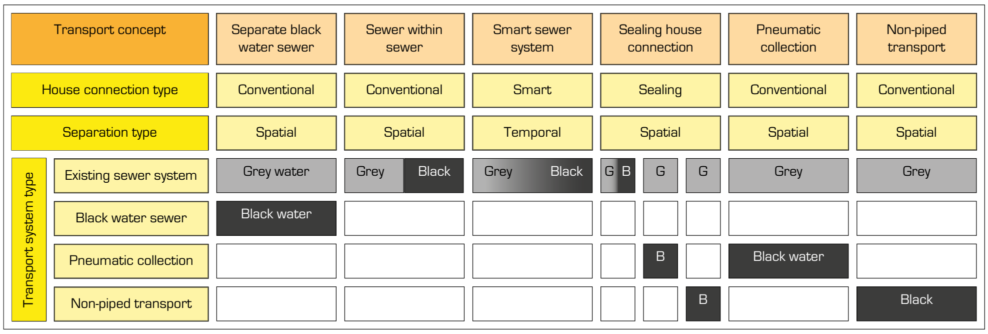
FIGURE 22 OVERVIEW ON THE CHARACTERISTICS AND APPLICABILITY OF SOURCE-SEPARATION CONCEPTS



	Source-separation concept	Modification in crawl space	Pipe within pipe	Retrofit of dual pipe system	Smart house connection	Sealing toilet	Greywater to the storwater drain
	Point of source-separation	Appliance	Appliance	Appliance	House connection	Appliance	Appliance
	Type of source-separation	Spatial	Spatial	Spatial	Temporal	Spatial	Spatial
	House connection	Existing + New	Existing + New	(Existing) + New	New (Smart)	Existing	Existing
	Toilet type	Conventional	Vacuum toilet	Vacuum	Conventional	Sealing toilet	Conventional
	Modifications inside buildings	None	Piping + toilet	Piping (+ toilet)	None	Toilet	Piping
Drainage system type	Existing drainage	Grey ▒	Grey	Grey	Grey ▒ Black	▒ ▨ ▨	Grey Black
	New drainage system	Black Black	Black ▨■	Black ▨■			
	Pneumatic collection					■	
	Non-piped transport					■	
Applicability to buildings	Ground floor housing	Partially	Yes	Yes	Yes	Yes	Yes
	Apartment complexes	No	Yes	Yes	Limited	Yes	Yes
	Public buildings	No	Yes	Yes	Limited	Yes	Yes
	Commercial office	No	Yes	Yes	Limited	Yes	Yes

Note that the toilet outside apartment concept is not explicitly included in this overview. Reading instruction: In the 'pipe within pipe' source-separation concept, for example, separation takes place on the level of the sanitary appliances, that is, streams are separated upon entering the drainage system. The separation is spatial and the concept requires an additional house connection for the second stream. The concept requires vacuum toilets and also involves modifications to the drainage system (piping) inside the building. Either grey water is conducted in the existing pipe and black water in the new pipe, or both grey and black water are conducted in new pipes. The concept is suitable for all different building types listed.

FIGURE 23 OVERVIEW ON THE CHARACTERISTICS OF TRANSPORT CONCEPTS

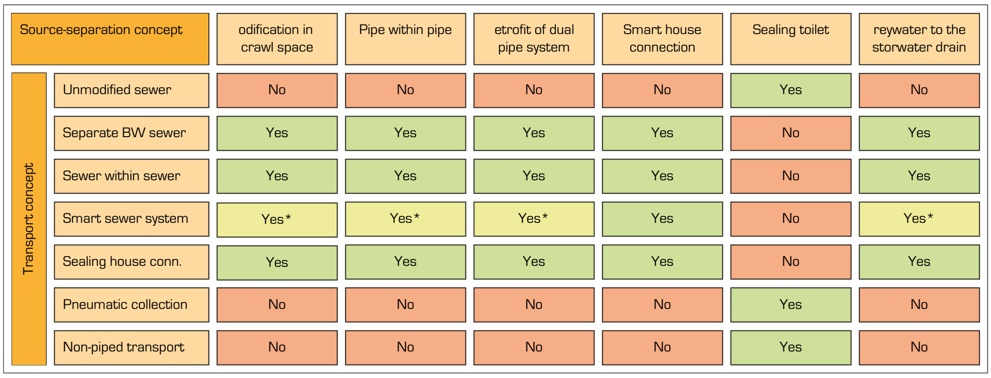


	Transport concept	Separate black water sewer	Sewer within sewer	Smart sewer system	Sealing house connection	Pneumatic collection	Non-piped transport
	House connection type	Conventional	Conventional	Smart	Sealing	Conventional	Conventional
	Separation type	Spatial	Spatial	Temporal	Spatial	Spatial	Spatial
Transport system type	Existing sewer system	Grey water	Grey Black	Grey ▒ Black	G B G G	Grey	Grey
	Black water sewer	Black water					
	Pneumatic collection				B	Black water	
	Non-piped transport				B		Black

Reading instruction: The 'smart sewer system' transport concept requires a specific smart house connection and separation of streams is temporal. Both grey and black water are conducted in the existing sewer system. The gradient from light grey to dark grey indicates that there is no sharp separation and mixing may take place with this concept.

The compatibility of source-separation and transport concepts is shown in Figure 24.

FIGURE 24 **OVERVIEW ON THE COMPATIBILITY AND SENSIBILITY OF COMBINATIONS OF SOURCE-SEPARATION CONCEPTS AND TRANSPORT CONCEPTS**



Source-separation concept		odification in crawl space	Pipe within pipe	etrofit of dual pipe system	Smart house connection	Sealing toilet	reywater to the storwater drain
Transport concept	Unmodified sewer	No	No	No	No	Yes	No
	Separate BW sewer	Yes	Yes	Yes	Yes	No	Yes
	Sewer within sewer	Yes	Yes	Yes	Yes	No	Yes
	Smart sewer system	Yes*	Yes*	Yes*	Yes	No	Yes*
	Sealing house conn.	Yes	Yes	Yes	Yes	No	Yes
	Pneumatic collection	No	No	No	No	Yes	No
	Non-piped transport	No	No	No	No	Yes	No

*Note that the toilet outside the apartment concept is not explicitly included. Fields marked with * indicate that concepts are compatible, but the respective combination would not be reasonable since streams that are fully separated are subject to risk of mixing after separation.*

4

EVALUATION AND DISCUSSION

In this chapter, functional requirements of sanitation and additional criteria for the evaluation of sanitary infrastructures are outlined. Based on these requirements and criteria, the current practice of wastewater management as well as potential scenarios for separate collection and transport of black water are qualitatively discussed. Moreover, possible indicators for quantitative assessment are suggested. Finally, source-separation is examined from a broader perspective.

4.1. FUNCTIONAL REQUIREMENTS AND EVALUATION CRITERIA

Functional requirements describe a condition or capability that a system has to satisfy, fulfil or comply with. A selection of functional requirements of sanitary infrastructures is summarised in Table 1. The strict formulation is very clear about the goals, whereas the pragmatic formulation leaves considerable room for interpretation. When it comes to the valuation of functional requirements of sanitation and their interpretation, two different approaches are conceivable: the anthropocentric perspective and ecologically conscious perspective. Depending on the perspective, interpretation of the pragmatic formulation of particular functional requirements will be rather strict or rather lax.

TABLE 1 **FUNCTIONAL REQUIREMENTS OF SANITARY INFRASTRUCTURE**

Functional requirement	*Strict formulation (ecologically conscious)*	*Pragmatic formulation (anthropocentric)*
Public hygiene	Prevention of water-borne diseases.	Prevention of water-borne diseases.
Flood prevention	Prevention of urban flooding.	Minimisation of the damage caused by urban flooding.
Water quality	Prevention of any pollution of receiving water bodies.	Minimisation of the pollution of receiving water bodies.
Resource recovery	Full resource recovery.	Maximisation or optimisation of resource recovery.
Pollutant control	Strict source control. Prevention of discharge of hazardous substances through the urban drainage system.	Partial source control. Limitation of discharge of hazardous substances through the urban drainage system.
Sustainability	Wastewater management must be sustainable.	Wastewater management must be as sustainable as possible.
Comfort	The system must be at least as user friendly and comfortable as current sanitation systems.	The system should be as user friendly and comfortable as possible.

Whether functional requirements are compromised and to which extent depends on the technology available and the system choices made by society. Complementary to the functional requirements, a number of additional evaluation criteria can be considered. An overview on possible additional evaluation criteria for different sanitary infrastructure concepts is provided in Table 2.

TABLE 2 EVALUATION CRITERIA FOR SANITARY INFRASTRUCTURE CONCEPTS

Criterion	*Description*
Public health risks	Risk of exposure to pathogens or other substances with potential adverse effects to public health.
Social acceptance	Acceptance of a specific concept by the general public.
Social support	Support of a specific concept by the general public.
Mentality of the user	Mentality of the user required for purposeful usage of a specific system.
Robustness	Measure of how robust a system is towards insufficient maintenance.
Risk of failure	Measure of the risk of failure related to a certain system.
Vulnerability	Measure of how open a certain concept is to attack or damage.
Resilience	Measure of the ability of a system to return to normal operation after occurrence of a failure or irregular incident.
Serviceability	Measure of the amount of time a system is available to provide services.
Safety of operation	Measure of how safe a system is to operate (non-public health issues).
Manageability	Measure of how well a system can be operated.
Maintainability	Measure of how well a system can be maintained.
Controllability	Measure of how well a system can be controlled.
Mentality of the operator	State of mind of the system operator required for safe and reliable operation of a system.
Legal framework	Legal framework required for the implementation of a system.
Policy framework	Policy framework required for the implementation of a system.

4.2. EVALUATION OF SOURCE-SEPARATION AND TRANSPORT CONCEPTS

4.2.1. PUBLIC HEALTH RISKS

Public health risks related to the wastewater infrastructure normally arise upon contact of citizens with faecal pathogens. In conventional water-borne sanitation systems, corresponding events are flooding of public areas with black water or water contaminated by black water, or spillovers of central sewer overflows or emergency outfalls.

In source-separated systems, additional health risks may emerge in case of cross-contamination of separated streams resulting from misconnected toilets, leaking sealing bags, or the application of temporal source-separation concepts. Furthermore, pathogens of faecal and other origin might enter the grey water system by other paths. It therefore seems indicated to assume faecal contamination in grey water streams until proven otherwise. As long as source-separation is only partially introduced and thus grey water is still mixed with black water to some extent, misconnection of source-separated toilets does not pose an additional threat to public health. Alternative transport systems, such as pneumatic transport systems and non-piped transport systems, raise several new questions relating to public health. In case of a multi-purpose pneumatic transport system, other solid waste types can potentially be contaminated by faecal pathogens.

A quantitative assessment of public health risk for different source-separation and transport concepts requires a detailed risk study. Such a study has been conducted by ten Veldhuis et al. (2010) for microbial risks associated with exposure to pathogens in contaminated urban flood water.

4.2.2. SOCIAL ACCEPTANCE, SOCIAL SUPPORT, MENTALITY OF THE USER

The current system of water borne-sanitation is broadly accepted and supported by the general public: water closets are comfortable and the flush and forget mentality linked to their usage is very convenient. Whether new sanitation concepts will be accepted and supported by the general public will largely depend on the comfort and user friendliness provided by the new system, on how the general public perceives the sense of urgency of new approaches to wastewater management, and on how costly or cost neutral a certain new concept is for the single household. Hereby, the state of mind of the user plays an important role. Source-separation in residential buildings is expected to be most sensitive to acceptance and support. Any source-separation concept that is less user-friendly than the current system or which involves significant changes within buildings will be likely met with scepticism, unless the new goals are accepted and the necessity of changing the current system is recognised. In residential buildings, any concept that can be implemented with moderate changes to the interior of the building (i.e., modification in crawl space, smart house connection) has a good chance of acceptance and support. Introduction of concepts that involve considerable changes to the status quo (i.e., introduction of vacuum or sealing toilets) will likely have a more different starting position.

The only concepts that can be realised independent of the house-owners decisions are concepts where separation takes place outside of buildings and does not require any changes to the drainage infrastructure inside buildings. This is the case for the ‘Smart House Connection’ concept (see paragraph 3.2.4) and partly for the ‘Modifications in the Crawl Space’ concept (see paragraph 3.2.1). All other concepts require modifications to the building drainage system inside buildings and/or sanitary appliances inside buildings and as a consequence house-owners are involved in the decision process.

4.2.3. ROBUSTNESS, VULNERABILITY, RESILIENCE, SERVICEABILITY, FAILURE RISK

Current wastewater infrastructure is generally fairly robust, given that the system can still be operated in a somewhat deteriorated state. However, blockages of gully pots or other system components may lead to flooding in public areas or buildings, or discharge of raw wastewater via central sewer overflows or emergency outfalls. Gravity systems are widely untouched by electrical power outages. Despite pump failure, water can still be discharged via central sewer overflows or emergency outfalls.

Mechanical sewer systems, especially pneumatic sewers (luchtpersriool) and vacuum sewers, are reported to be sensitive to malfunction due to mechanical and electrical failures (wRw, 2005). In pressurised systems, failure of non-return valves located between pump pits and the pressure main can be of concern. In vacuum system, leakage due to a defective system component can be of concern. For non-gravity systems in general, the vulnerability to power outages is an important potential issue.

In pressurised systems, local power outages or failure of a pump or compressor does not affect the remaining network. However, discharge of wastewater from houses affected by the failure or power outage will no longer be possible. Local collection tanks will eventually overflow or cause a backing-up of wastewater in the drainage system inside the building.

In vacuum systems, a defective component leading to a leakage of the system will cause the whole system to be out of operation until the leak is located. Yet the functioning of vacuum toilets and vacuum drainage systems remains unaffected by local power outages. Power only needs to be available to the central vacuum station. None of the sanitary appliances served by the vacuum system will be able to discharge any significant amounts of wastewater in case of power outage at the central vacuum station, unless the vacuum station is equipped with a backup power source. If vacuum sewers start outside buildings and transport inside buildings is by gravity, water can still be discharged to the local collection tanks. These will eventually overflow or cause a backing-up of wastewater in the drainage system inside the building.

Sealing toilets may require electrical energy for the process of sealing the human excreta into tight bags. Toilets will be out of operation in case of a local power outage, unless equipped with a backup power source.

A comprehensive study of vulnerability, robustness, failure modes and a resulting quantification of the risk of failure and the serviceability of different systems could be achieved by, for example, a fault tree analysis.

4.2.4. SAFETY OF OPERATION

Safety of operation refers to any potential threat not related to public health issues emerging from a collection or transport system. Conventional gravity sewers, pressure sewers, vacuum sewers and pneumatic waste collection systems are all relatively safe to operate. The main safety risk is the collapse of pipes leading to a gap in the pavement. On the other hand, pneumatic sewers involve compressors that are subject to considerable interior pressures and therefore pose a potential threat in case of an explosion of the compressor. Other potential safety risks can emerge from septic sewer gas or electrified components of the sewer system.

4.2.5. MANAGEABILITY, CONTROLLABILITY, MAINTAINABILITY, MENTALITY OF THE OPERATOR

Conventional gravity systems can be managed and maintained using either reactive maintenance or planned maintenance. Mechanical sewers and pneumatic waste collection systems on the other hand require a certain amount of planned maintenance (WEF, 2008). Systems requiring regular proactive maintenance require a corresponding state of mind of the system operator in order to prevent inevitable system outages.

4.2.6. LEGAL AND POLICY FRAMEWORK

The legal and policy framework has a considerably influence on the concepts that can or cannot be implemented. Accordingly, the current policy and legislative framework should be adapted in such a way that new creative solutions are permitted if the key functional requirements are fulfilled. Furthermore, the legal and policy framework can provide incentives towards the implementation of source-separation in general, or a specific concept in particular.

FACILITATION OF SOURCE-SEPARATION INSIDE BUILDINGS

Source separation inside buildings requires the consent of house-owners. System changes will likely be implemented by house-owners if they expect some kind of benefit (e.g., financial, aesthetic, functional, comfort). Areas with mostly ground floor housing are characterised by a large number of house owners involved in decisions about modifications to the existing drainage infrastructure inside buildings. Some house owners may be willing to make changes to the existing drainage structure inside their houses, others might be willing to do so as long as they don't have to cover the costs, whereas again others might totally refuse it. Apartment complexes often belong to housing associations. Decisions pertaining to the implementation of new concepts are thus not made by the inhabitants of a flat, but will still be influenced by what the owner of the flat perceives as positive impact on the rental value of the flat. Office buildings are similar to apartment complexes in terms of technical possibilities and decision-making. The situation in public buildings is somewhat different. Viable implementations depend on the type of building and the type of transport system that will be made available outside buildings. Facilitation of source-separation inside buildings implies that the transition to source separation will be gradual and that substantial fractions of toilet water will still be discharged through the existing drainage system over an extended period in the future.

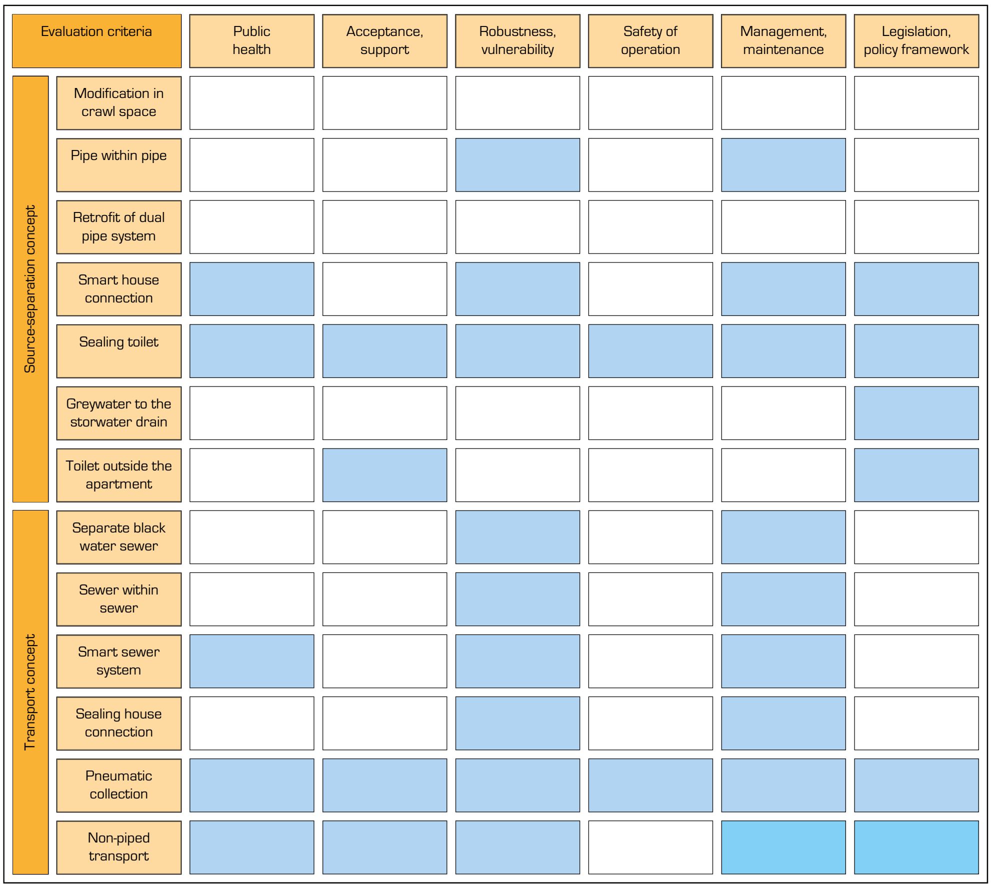
COMPULSORY INTRODUCTION OF SOURCE-SEPARATION INSIDE BUILDINGS

Depending on the legislative and policy framework, house-owners could be obliged to implement measures for source-separation inside buildings. The concepts applied depend on housing type and the transport system outside buildings. Essentially, compulsory introduction of source-separation is similar to facilitation of source- separation in terms of possible implementations, but the transition to full source- separation can be substantially accelerated.

4.2.7. SYNTHESIS AND OVERVIEW

Both source-separation and transport concepts are subject to a number of open questions pertaining to various aspects discussed in this chapter. Figure 25 graphically summarises which concepts are subject to which types of open questions.

FIGURE 25 **OVERVIEW ON OPEN QUESTIONS RELATED TO SOURCE-SEPARATION AND TRANSPORT CONCEPTS**



Evaluation criteria		Public health	Acceptance, support	Robustness, vulnerability	Safety of operation	Management, maintenance	Legislation, policy framework
Source-separation concept	Modification in crawl space	⬜	⬜	⬜	⬜	⬜	⬜
	Pipe within pipe	⬜	⬜	🟦	⬜	🟦	⬜
	Retrofit of dual pipe system	⬜	⬜	⬜	⬜	⬜	⬜
	Smart house connection	🟦	⬜	🟦	⬜	🟦	🟦
	Sealing toilet	🟦	🟦	🟦	🟦	🟦	🟦
	Greywater to the storwater drain	⬜	⬜	⬜	⬜	⬜	🟦
	Toilet outside the apartment	⬜	🟦	⬜	⬜	⬜	🟦
Transport concept	Separate black water sewer	⬜	⬜	🟦	⬜	🟦	⬜
	Sewer within sewer	⬜	⬜	🟦	⬜	🟦	⬜
	Smart sewer system	🟦	⬜	🟦	⬜	🟦	⬜
	Sealing house connection	⬜	⬜	🟦	⬜	🟦	⬜
	Pneumatic collection	🟦	🟦	🟦	🟦	🟦	🟦
	Non-piped transport	🟦	🟦	🟦	⬜	🟦	🟦

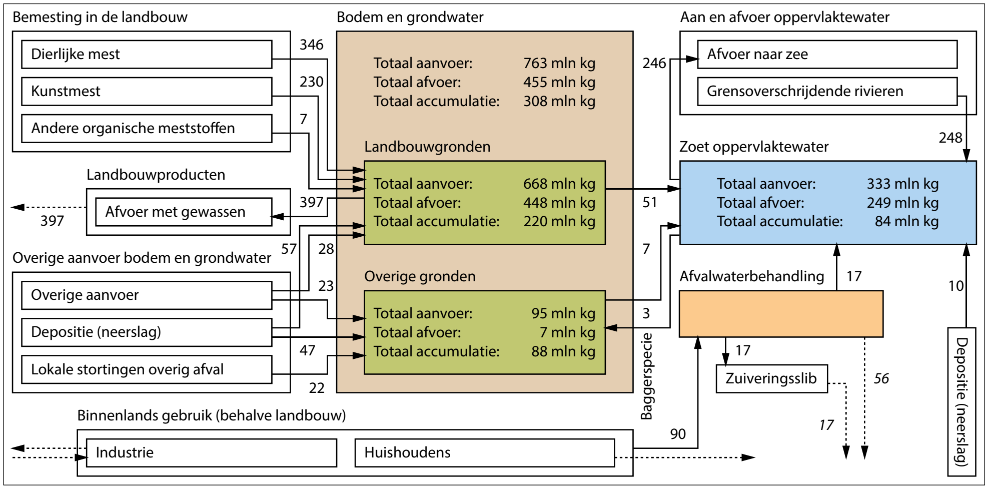
Different types of open questions related to different source-separation and transport concepts. Blue boxes indicate that there are considerable open questions of a specific type for a specific concept. White boxes indicate that there are no or only minor open questions of a specific type for a specific concept.

4.3. SOURCE-SEPARATION IN A BROADER CONTEXT

4.3.1. THE CONTRIBUTION OF NUTRIENT RECOVERY

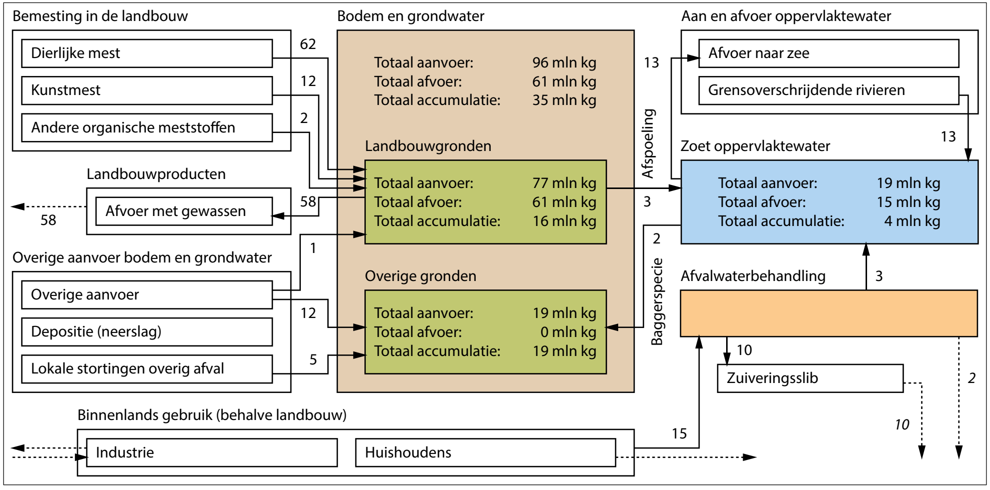
In the Netherlands, some 89,310 tons of nitrogen and 14,951 tons of phosphorus per year flow towards treatment plants (CBS, 2010) from where they are discharged to surface water bodies, released to the atmosphere, or end up in the ash of incinerated sludge. These flows are shown in a broader context in Figure 26 and Figure 27.

FIGURE 26 **OVERVIEW ON NITROGEN FLOWS IN THE NETHERLANDS**



Data represent the yearly total flows in 2008 published by CBS. Flows are in mln kg. Note that the several flows are missing. Data on these flows were not available.

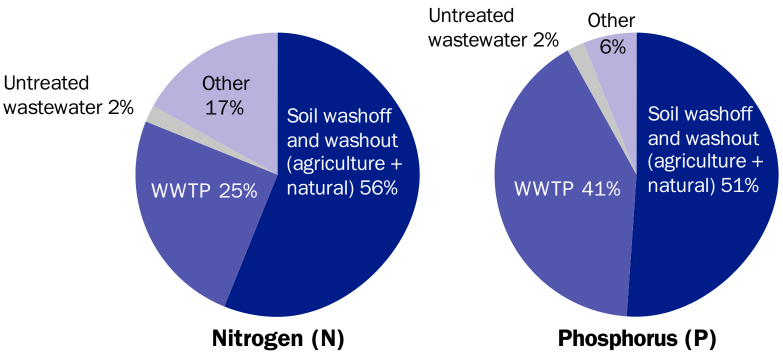
FIGURE 27 **OVERVIEW ON PHOSPHORUS FLOWS IN THE NETHERLANDS**



Data represent the yearly total flows in 2008 as published by CBS. Flows are in mln kg. Note that the several flows are missing. Data on these flows were not available.

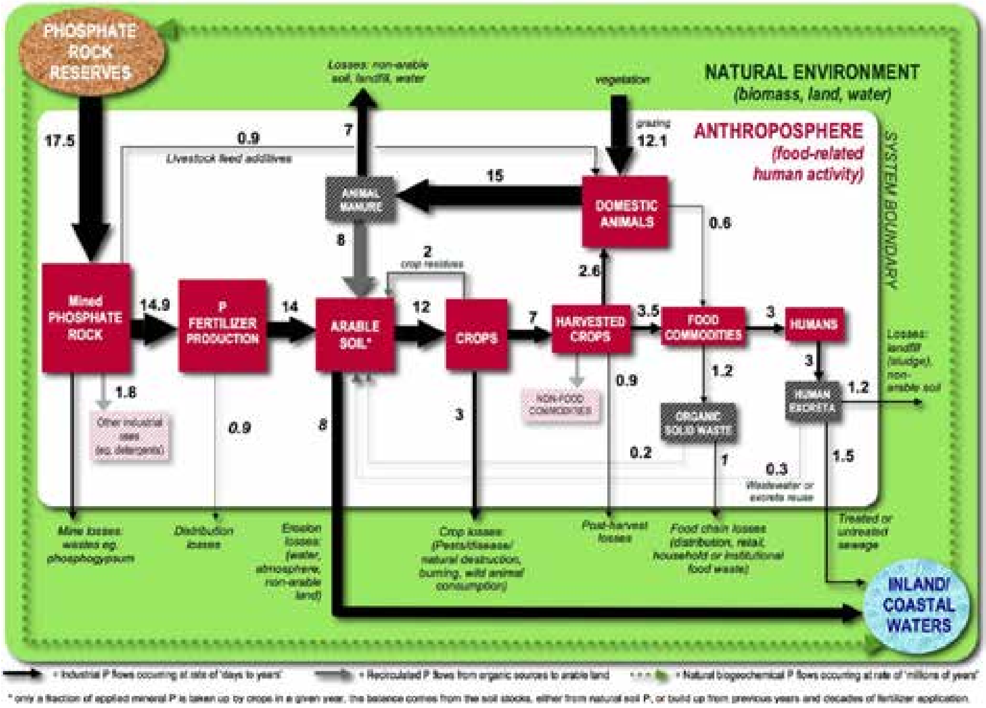
The contribution of nutrient discharge from wastewater treatment plants into surface waters is considerable, as is illustrated in Figure 28.

FIGURE 28 **ORIGIN OF NUTRIENTS IN DUTCH SURFACE WATERS (SOURCE: STICHTING RIONED)**



The mineral fertiliser demand of the Dutch agricultural sector in 2008 amounted to 230,000 tons of nitrogen and 12,000 tons of phosphorus (CBS, 2010). From this perspective, especially the amount of phosphorus discharged in municipal wastewater is substantial. However, the use of mineral fertiliser used by the Dutch agricultural sector is not necessarily equivalent to the amount of mineral fertiliser required for the production of the food consumed in Dutch households. On the one hand, food or food concentrates for livestock can be imported from outside the Netherlands. On the other hand, nutrients originating from mineral fertiliser can be present in food or food concentrates for livestock intended for export. To this end, phosphorus flows through the global food production and consumption system are to be consulted (Figure 29).

FIGURE 29 **KEY PHOSPHORUS FLOWS THROUGH THE GLOBAL FOOD PRODUCTION AND CONSUMPTION SYSTEM (SOURCE: CORDELL ET AL., 2009)**



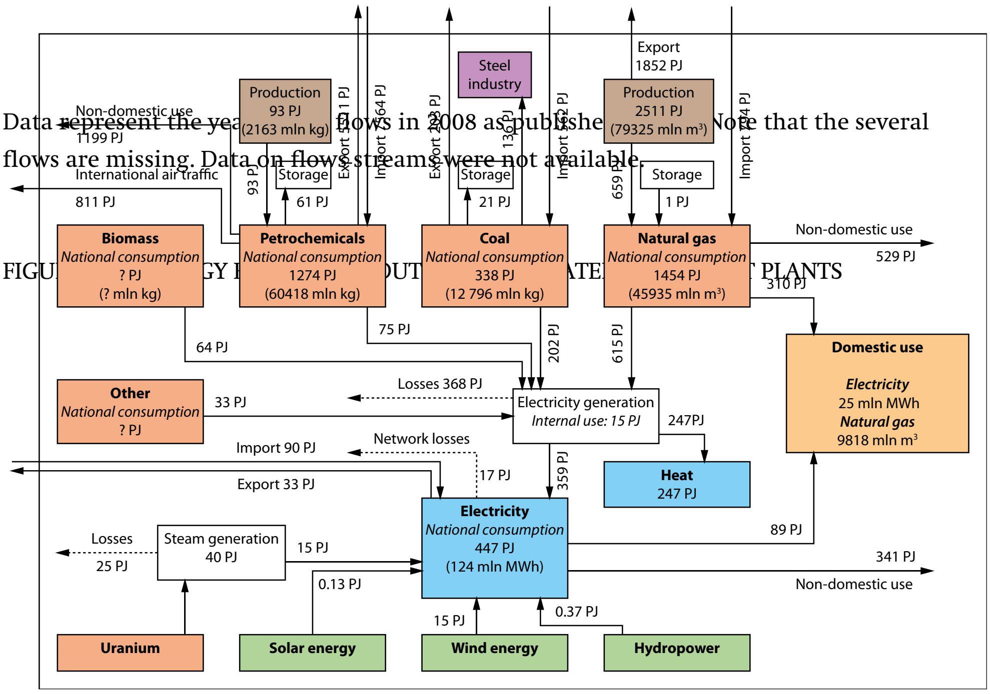
Key phosphorus flows through the global food production and consumption system, indicating phosphorus usage, losses and recovery at each key stage of the process. Units are in Million Tonnes per year (Only significant flows are shown here, relevant to modern food production and consumption systems.). Source: Cordell et al. (2009).

On a global scale, phosphorus discharged in domestic wastewater can replace only about one sixth of the total rock phosphate mining. The rest of the phosphorus is lost to the environment due to several processes between mining of phosphate rock and consumption of food products. In view of the emerging problem of phosphorus depletion, nutrient recovery from human excreta may become inevitable in the medium to long term. However, it will not be the only means of mitigation and must be accompanied by other measures.

4.3.2. THE CONTRIBUTION OF ENERGY RECOVERY

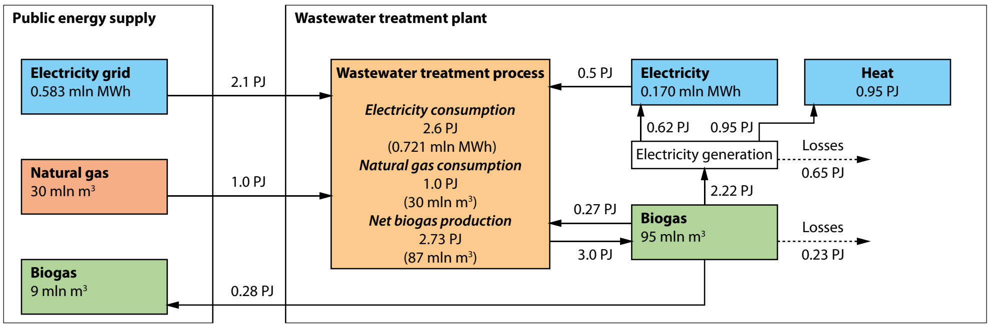
The total energy demand of the Netherlands in the year 2008, as well as energy production and demand of wastewater treatment plants are summarised in Figure 30 and Figure 31, respectively.

FIGURE 30 **ENERGY BALANCE OF THE NETHERLANDS**



Data represent the yearly total flows for all wastewater treatment plants in 2008 as published by CBS. Note that the several flow are missing. Data on these flows were not available.

FIGURE 31 **ENERGY BALANCE OF DUTCH WASTEWATER TREATMENT PLANTS**



Data represent the yearly total flows for all wastewater treatment plants in 2008 as published by CBS. Note that the several flow are missing. Data on these flows were not available.

The operational energy required by all wastewater treatment plants in the Netherlands amounts to roughly 3.7 PJ per year (STOWA 2010-35). If conversion losses from primary energy carriers and biogas to electricity are accounted for, the yearly demand amounts to 8 PJ of primary energy and biogas. The energy delivered to the public energy supply amounts to roughly 0.3 PJ per year in the form of biogas. The net primary energy and biogas demand for wastewater treatment hence amounts to 7.7 PJ per year. This is roughly equivalent to 0.23% of the total yearly energy consumption in the Netherlands, or 1.9% of the total yearly domestic energy consumption in the Netherlands. From this perspective, the potential of energy recovery from wastewater seems marginal. On the other hand, the net primary energy and biogas demand is about 50% of the amount of electrical energy produced by solar power, wind power and hydropower together. From this perspective, the potential of energy savings and energy recovery facilitated by anaerobic technology on source- separated wastewater streams is substantial.

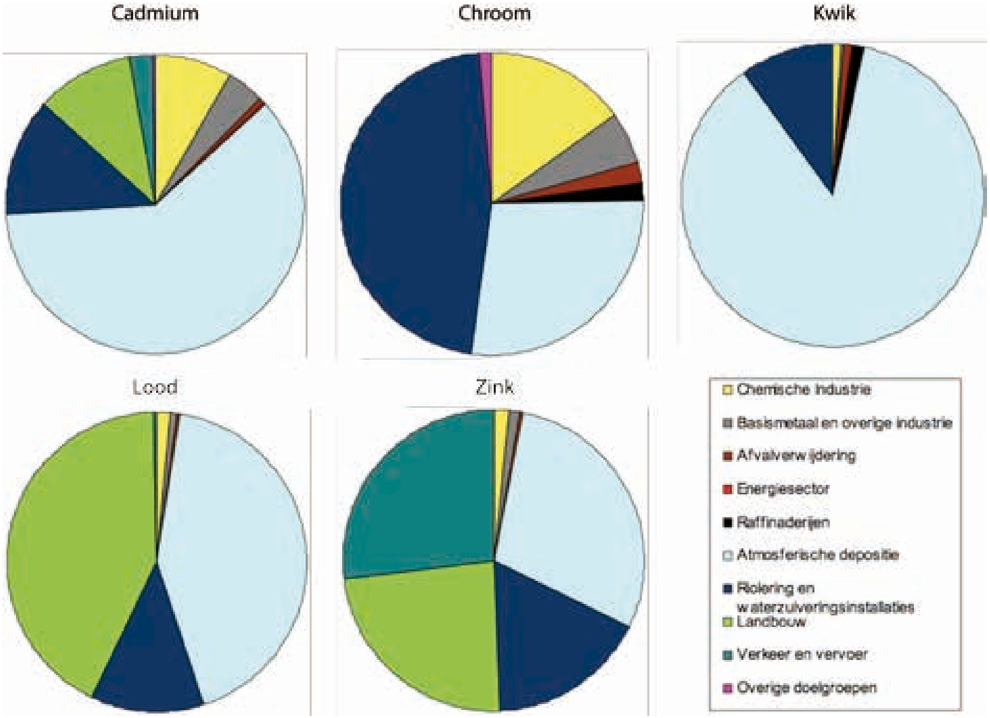
4.3.3. THE CONTRIBUTION OF MICROPOLLUTANT REMOVAL

Private households are the main source for most human pharmaceuticals, hormones, biocides, ingredients of personal care products and food ingredients to enter municipal wastewater.

HEAVY METALS

The contribution of current wastewater management to heavy metal emissions to surface water bodies is shown in Figure 32.

FIGURE 32 HEAVY METAL EMISSION TO SURFACE WATER BODIES IN 2007 (SOURCE: RIVM, 2010)



Wastewater management in most cases is not the main source of heavy metals in surface water bodies, but the contributions are still significant. Moreover, it must be recalled that most of the heavy metals accumulate in the sludge during wastewater treatment and overall only 15% of the heavy metal load is discharged with the effluent.

PHARMACEUTICALS, PHARMACEUTICAL RESIDUES AND HORMONES

Pharmaceuticals, pharmaceutical residues and hormones are dispersed to the environment through domestic wastewater and application of animal manure to agricultural soils. Hospitals and pharmaceutical companies are point sources for domestic wastewater. The contribution of households is more diffuse. Removal of hormones, pharmaceuticals and metabolites thereof in current wastewater treatment plants is limited, and removal takes place mainly via sorption and biological degradation. Joss et al. (2008) furthermore point out that 5% to 20% of sewage is discharged to the environment before treatment due to sewer leakage and combined sewer overflow. This can lead to contamination of both surface water and ground water bodies. Overall, wastewater management is the main disposal route for human hormones, pharmaceuticals and pharmaceutical residues.

Veterinary pharmaceuticals and hormones, however, are an important other diffuse source of pharmaceuticals in the aquatic environment; they are dispersed to the environment during application of animal manure to agricultural soils. Pharmaceutical residues can then enter surface water bodies after washout from agricultural soils, or contaminate ground water bodies after infiltration of contaminated seepage water.

Summing up, comprehensive removal of pharmaceuticals and pharmaceutical residues from domestic wastewater tackles one important dispersion route. Extensive reduction of the input of pharmaceuticals to the aquatic environment, however, also requires certain measures to reduce the input of the second dispersion route, namely the agricultural sector.

5

OUTLOOK

Alternative sanitation systems are generally advocated based on (1) their potential contribution to energy savings, (2) potential recovery of nutrients from domestic waste streams, and (3) potential removal of micropollutants present in domestic wastewater. Source-separated sanitation systems are one flavour to alternative sanitation systems. In the introduction to this report, it was argued that research projects on source- separation so far have mainly focused on the treatment of separated streams, and that pilot projects were limited to sustainable new building projects for the most part. This report, in contrast, suggests that integration of source-separated collection is also thinkable and discussable in the existing urban water infrastructure. Yet the concepts exposed in this report are at different stages as to their state of maturity and implementation. Whereas some are merely theoretical concepts, others have already been shown to be practically feasible. Further advances towards source-separation in the existing urban water infrastructure, or alternative sanitation systems in general, are closely linked to a number of questions and aspects.

DRIVING FORCES AND CHANCES FOR IMPLEMENTATION

There are two important elements that influence the rate at which alternative sanitation systems may be implemented. The first important group of driving forces are legislative and societal requirements formulated towards wastewater management. With regard to surface water quality, the current trend is to enforce tertiary treatment in order to further reduce pollutant loads from wastewater treatment plants. In the broader political agenda, energy recovery and climate neutral wastewater management is at the centre of attention. However, phosphorus as constituent of interest and micropollutants as constituents of concern (particularly hormones, pharmaceuticals and pharmaceutical residuals) might become increasingly important in the future. Attempts to recover nutrients from waste streams and to tackle the problem of micropollutants may act as additional drivers towards the implementation of alternative sanitation systems.

The second important group of driving forces towards alternative sanitation systems are the need for renovation and rehabilitation of existing urban areas and/or the existing urban water infrastructure. The efforts required for the renovation and rehabilitation of the existing urban water infrastructure on the short term are substantial. The need for sewer renovation and rehabilitation can be intensified by local soil conditions, which are in a large part of the Netherlands the driving force for sewer rehabilitation. This need for renovation and rehabilitation of municipal sewer systems is a key chance for the implementation of alternative transport concepts outside buildings. On the other hand, renovation works within existing buildings or redevelopment of whole residential or commercial neighbourhoods are key chances for the implementation of alternative collection concepts inside buildings.

IMPLICATIONS FOR THE SANITARY INFRASTRUCTURE

Renewal of existing urban water infrastructures and integration of alternative concepts will likely lead to a diversification of urban drainage systems towards solutions that are more flexible in space and time. As suggested by Berlamont (2004), general guidelines applicable for all urban drainage systems will need to be replaced by urban drainage engineering that takes into account local characteristics and limitations. There are good reasons to rethink the urban water infrastructure, and obviously there are plenty of opportunities for implementing more flexible alternative sanitation systems. But, are we ready for it?

OPEN QUESTIONS AND FURTHER STEPS

Open questions and opportunities for further research are almost as abundant as the opportunities for system adaptations. On a general level, open questions relate to the efficacy and desirability of source-separated sanitation systems:

- Given a set of functional requirements (e.g., nutrient recovery, removal of micropollutants, flexibility), are source-separated systems effective and efficient in achieving the goals set?
- Are there other alternative sanitation systems or modifications to conventional systems that are equally or more effective and efficient?

On a more detailed level, open questions pertain to the technical implementation of the source-separation concepts proposed, and to the evaluation thereof:

- How could the different components of a specific source-separated concept (e.g., sealing toilets, smart house connections) look like?
- How can different evaluation criteria (e.g., manageability, risk of failure, system performance, etc.) be measured and made tangible?

With respect to separate collection and treatment of black water in particular, the following open questions for research are identified:

- How do the type of toilet and the way it is used, the type of collection system on the premises, and the type of transportation system to a (semi-centralised) treatment facility influence the characteristics of black water (in terms of transportability and treatability)?
- To what extent are the design of in-house appliances, collection and transportation modes, and treatment options related to each other?

The intermittent character of black water production also requires research on the issues of scale (e.g., the black water production at household level may peak during a party, but be zero during summer holidays). Following main research question is identified:

- What scale is necessary to be able to adequately collect, transport and treat black water given the diurnal, weekly and seasonal variations in black water production?

Part of these questions can be answered by desk studies, part of these questions have to be addressed in monitoring pilots.

RECOMMENDATIONS

Generally, it is recommended that source-separation in the existing urban water infrastructure is seriously considered as one possible alternative sanitation system. Furthermore, chances for implementation of such systems arising upon renewal of the urban water infrastructure should be utilised properly. It is suggested that the development of alternative sanitation concepts takes an integral view on wastewater management, rather than separately thinking about toilet, sewer system, and wastewater treatment. To achieve this, it is important that urban drainage experts work alongside wastewater treatment experts in the development of alternative concepts. Ideally, tackling transport-related questions in alternative systems can at the same time elucidate transport-related problems in the remaining conventional sanitation systems. Finally, it is proposed that system flexibility is an important dimension in developing alternative sanitation concepts. System flexibility will facilitate a rapid adaptation to changing requirements and constraints formulated towards the urban water infrastructure.

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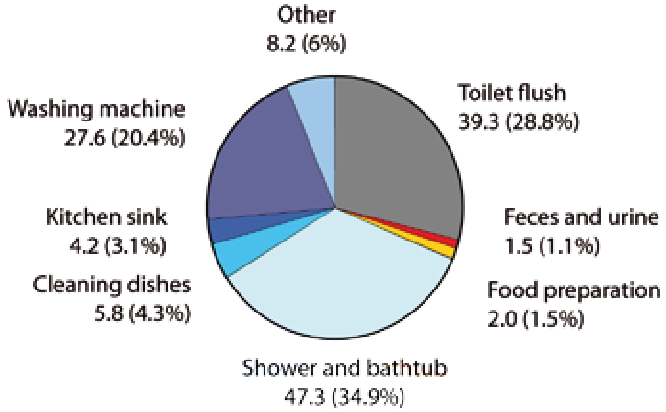
A

CONSTITUENTS OF DOMESTIC WASTEWATER

WATER

Water is the main constituent of domestic wastewater and transport agent for all other constituents of interest. The origin of water from different domestic appliances and usages is depicted in Figure 1. It is remarkable that black water originating from toilets amounts to one third of the domestic wastewater production, although human excreta alone are only a tiny fraction of the total wastewater volume. A further dilution of human excreta takes place upon combination with grey water, mixing with rainwater or industrial wastewater, or influx of groundwater. Water as constituent is interesting due to its reuse potential. The significance of water reclamation ranges from negligible to essential, depending on the degree of water scarcity in a specific region.

FIGURE 1 **WASTEWATER PRODUCTION OF DIFFERENT SANITARY APPLIANCES (SOURCE: STOWA 2008-03)**



ENERGY

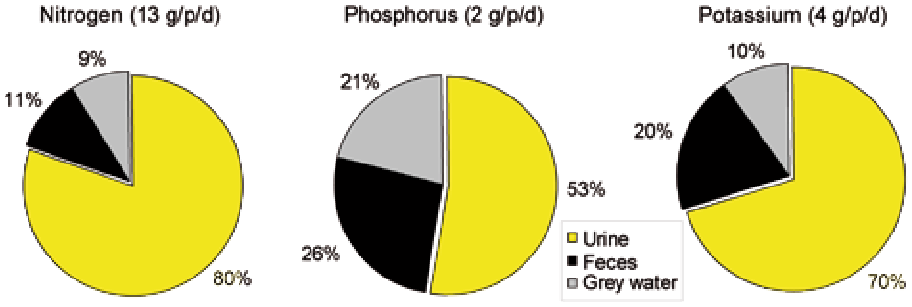
Domestic wastewater contains energy in the form of thermal and chemical energy. Thermal energy is a result of the usage of heated water, whereas chemical energy is mainly linked to human excreta and organic kitchen waste entering the sewer. The yearly discharge from households in the Netherlands amounts to 49 PJ for thermal energy1 and 11 PJ for chemical energy. Overall, black water contains just over 10 percent of the thermal energy but most of the chemical energy convertible to a useful form of energy (e.g., heat energy, mechanical energy, electrical energy) by means of for instance biogas production in anaerobic processes (STOWA 2010-35). Energy as constituent is interesting due to recent efforts towards energy efficiency, reduction of the carbon footprint and usage of renewable energy sources.

1 Based on an average temperature rise of 16°C from supply to sink. The amount of energy required for heating the water is higher than the thermal energy contained in the wastewater. The amount energy that can be recovered can be lower than the amount contained in the wastewater.

NUTRIENTS

Nutrients, particularly nitrogen, phosphorus and potassium originate mainly from human excreta, detergents and organic kitchen waste. The absolute and relative loads of different streams are depicted in Figure 2. Nutrients as constituents are of concern on the one hand due to the potential adverse effect on aquatic environments, and are of interest on the other hand due to growing ambitions of nutrient recovery and reuse. Currently, mainly nitrogen and phosphorus are at the centre of attention.

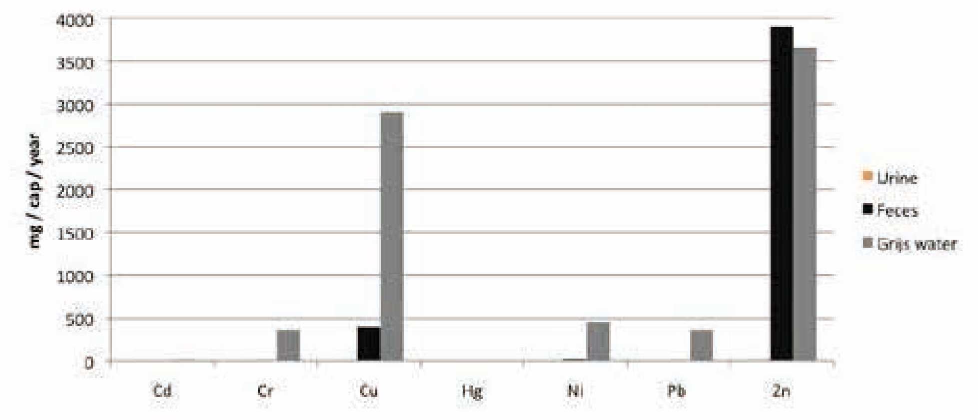
FIGURE 2 NITROGEN, PHOSPHORUS AND POTASSIUM IN DOMESTIC WASTEWATER (SOURCE: STOWA 2005-12)



HEAVY METALS

Heavy metals present in domestic wastewater originate from human excreta but also from plumbing and other sources, and possibly the drinking water itself. Overall, the highest loads of heavy metals are found in grey water. Significant amounts of copper and zinc are found in faeces. A graphical overview on heavy metal loads is provided in Figure 3. Heavy metals as constituents are of concern since they may accumulate in the soils of infiltration facilities in case of local treatment of grey water. In case of centralised treatment, heavy metals accumulate in the sludge produced during the treatment of wastewater (CBS, 2010a), thereby possibly rendering the sludge unsuitable for reuse in agriculture. Although most heavy metals are essential trace elements, they can be toxic if present in elevated concentrations.

FIGURE 3 HEAVY METAL LOADS IN DOMESTIC WASTEWATER (SOURCE: STOWA 2010-10)



MICROPOLLUTANTS

Micropollutants comprise a broad range of substances including pesticides, biocides, pharmaceuticals, hormones, constituents of personal care products, flame-retardants, perfluorinated compounds and many others. Micropollutants are of concern since they might be endocrine disrupters or have other adverse effects on the environment already in very low concentrations and potentially pose a threat to drinking water sources. In the context of domestic wastewater, mainly pharmaceuticals, hormones and constituents of personal care products are of concern. Pharmaceuticals can enter the domestic drainage system either via direct disposal to the wastewater drainage system or as pharmaceutical residuals in human excreta. These pharmaceutical residues are found in either the form of the original pharmaceutical or as metabolites thereof. Pharmaceutical residues are found in both urine and faeces whereas hormones are found mainly in urine.

PATHOGENS

The majority of pathogens are found in human excreta, but pathogens can also enter the drainage system through sanitary appliances other than toilets. The pathogenic organisms that can be found in domestic wastewater can be classified into four broad categories: bacteria, protozoa, helminth eggs, and viruses. Pathogens are of concern for they can be responsible for illness and diseases. In combination with the presence of pharmaceuticals and pharmaceutical residues in wastewater, concerns about the emergence of resistant pathogens are increasing.

B

EXEMPLARY PLANS OF EXISTING APARTMENT COMPLEXES

FIGURE 4 **SCHEMATIC DRAWING OF A BATHROOM STACK IN AN APARTMENT COMPLEX BUILT IN THE 1960'S**

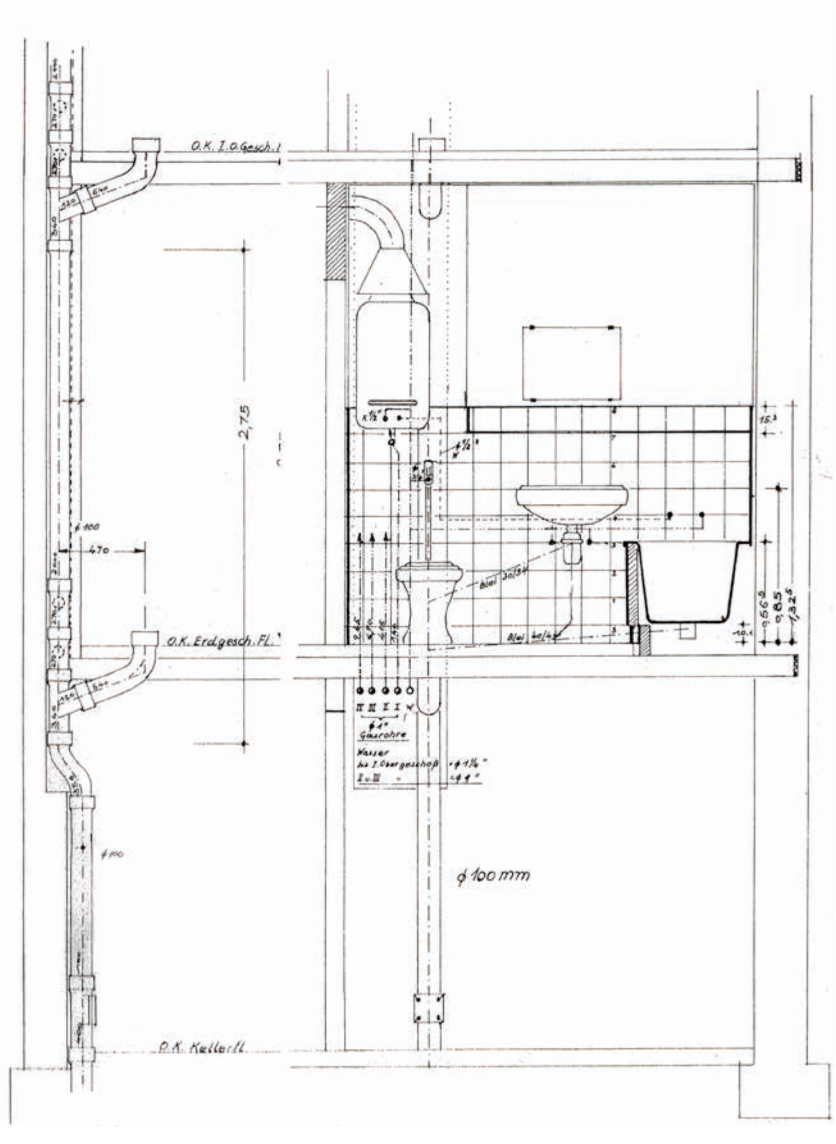
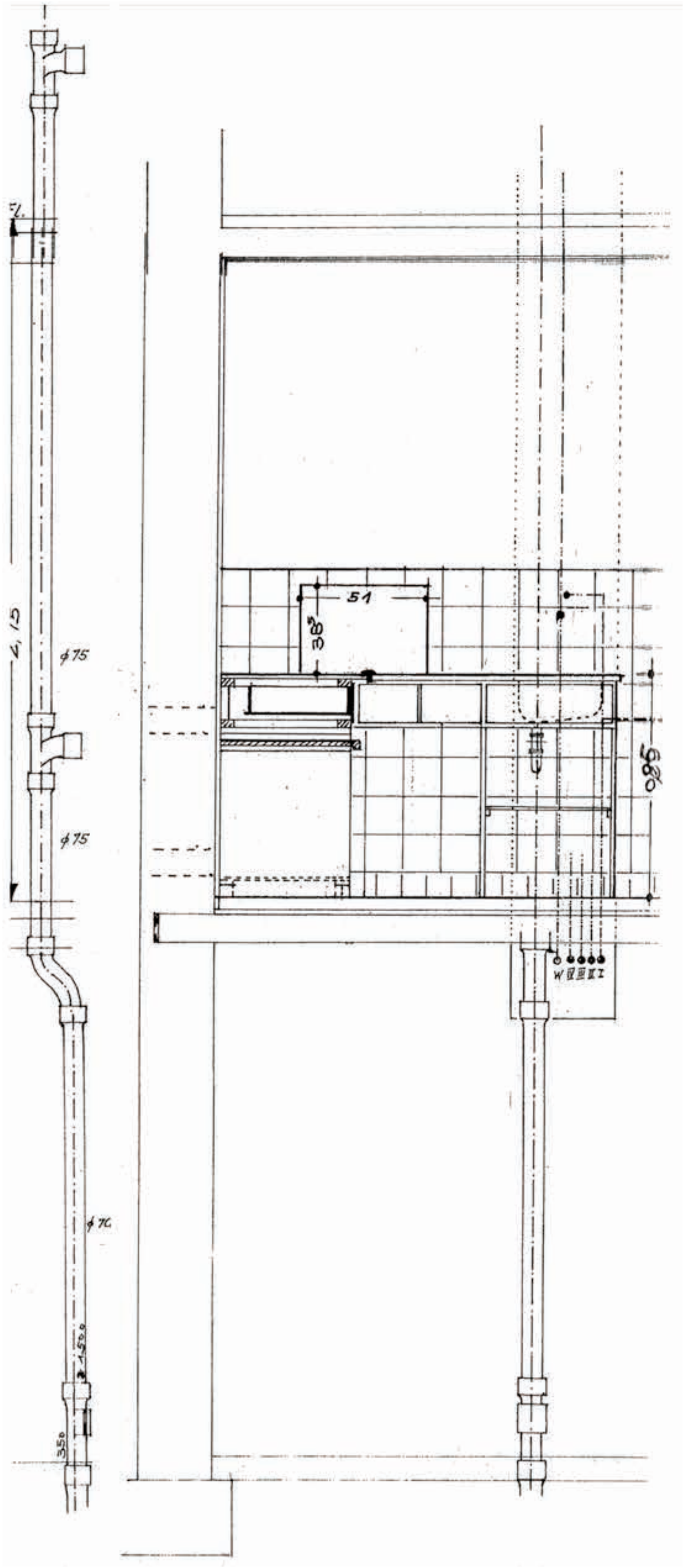


FIGURE 5 SCHEMATIC DRAWING OF A KITCHEN STACK IN AN APARTMENT COMPLEX BUILT IN THE 1960'S



C

SMART HOUSE CONNECTION CALCULATIONS

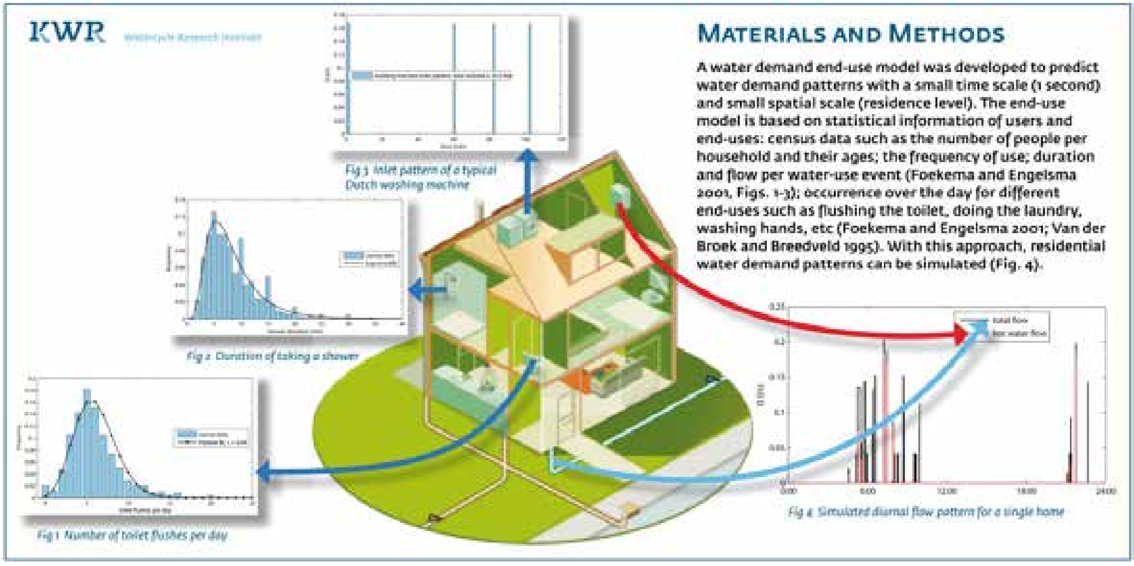
C.1. CALCULATION BASIS

Calculation basis for the estimation of the percentage of separate black water collection was the SIMDEUM model (**SIM**ulation of water **D**emand; an **E**nd-**U**se **M**odel) developed by Mirjam Blokker. Detailed information about this model can be found in the respective PhD thesis:

Blokker, 2010. Stochastic water demand modelling for a better understanding of hydraulics in water distribution networks. PhD Thesis, Delft University of Technology. ISBN 978-90-8957-015-4. Water Management Academic Press, Delft, 2010.

A brief summary of the SIMDEUM model is provided in Figure 6.

FIGURE 6 **SIMDEUM MODEL (SOURCE: KWR WATERCYCLE RESEARCH INSTITUTE)**



MATERIALS AND METHODS

A water demand end-use model was developed to predict water demand patterns with a small time scale (1 second) and small spatial scale (residence level). The end-use model is based on statistical information of users and end-uses: census data such as the number of people per household and their ages; the frequency of use; duration and flow per water-use event (Foekema and Engelsma 2001, Figs. 1-3); occurrence over the day for different end-uses such as flushing the toilet, doing the laundry, washing hands, etc (Foekema and Engelsma 2001; Van der Broek and Breedveld 1995). With this approach, residential water demand patterns can be simulated (Fig. 4).

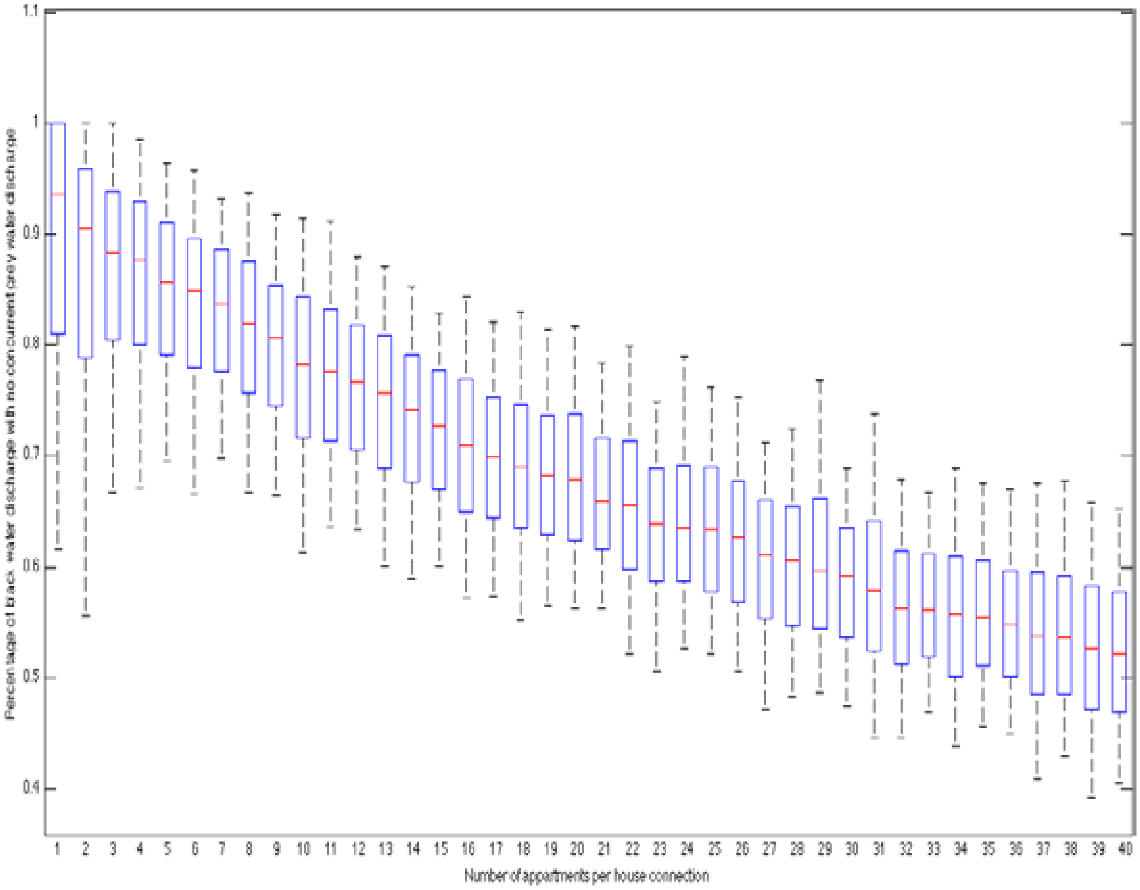
For the calculations regarding separate collection of blackwater, water demand patterns in SIMDEUM were replaced by wastewater discharge patterns. Based on these discharge patterns of domestic sanitary appliances, a set of hundred different generic household discharge patterns was generated. This set represents different daily discharge patterns of households with between 1 and 5 inhabitants and an average of
2.2 inhabitants per household. The author would like to thank Mirjam Blokker for making available these basic data for further processing.

C.2. FURTHER CALCULATIONS

Based on the basic data derived from the SIMDEUM model, the amount of toilet water that can be collected separately could be estimated. The first calculation aimed at estimating the fraction of toilet water that is discharged without concurrent discharge of grey water. Hereby, transport times and possible attenuation of flush waves in the drainage system inside buildings was not accounted for. To obtain a good insight into the variation due to different household characteristics and to the dependence on the number of households connected to the same house connection, following procedure was applied:

For 1 < n < 40, n households were randomly selected 1000 times, where n is the number of households connected to one house connection. Hence for every single number of households n, 1000 different values for the percentage of toilet water discharge without concurrent grey water discharge were obtained. These values were translated into a boxplot for every number of households (Figure 7).

FIGURE 7 **VOLUME OF BLACK WATER DISCHARGED WITH NO CONCURRENT GREY WATER DISCHARGE**



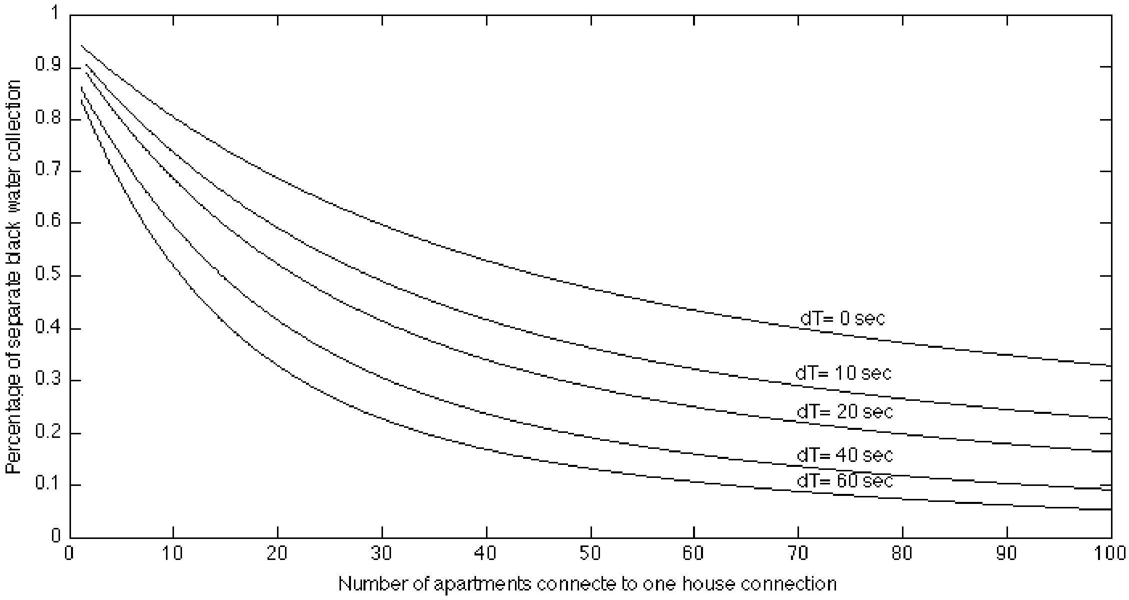
Each of the box plots indicates the minimum value, the lower quartile, the median, the upper quartile and the maximum value of the 1000 instantiations performed for the respective number of households. The variation reflects differences in water discharge represented by different households. Note that this graph corresponds to the situation dT=0 in Figure 8. Hence the corresponding mean value can be read from Figure 8. Reading instruction: in case one household is connected to a single house connection, between 62% and 100% of the black water are discharged with no concurrent discharge of grey water, the median is at 93%; in case 40 households are connected to a single house connection, between 40% and 65% of the black water are discharged with no concurrent discharge of grey water, the median is at 52%.

In the following step, the sensitivity to transport times was investigating by looking into the percentage of toilet water discharge, where no grey water transport takes place during and a certain time span before and after the toilet water discharge. To this end, time spans of 0, 10, 20, 40 and 60 seconds were considered.

For 1 < n < 100, n households were randomly selected 100 times, where n is the number of households connected to one house connection. Hence for every single number of households, 100 different values for the percentage of toilet water discharge without grey water discharge during, before or after toilet water discharge were obtained.

The mean of the respective 100 values per dT was taken and the graph plotting percentage of separate collection versus number of households per house connections were interpolated (Figure 8).

FIGURE 8 **ESTIMATION OF THE VOLUME OF BLACK WATER THAT CAN BE COLLECTED SEPARATELY**



Fitted curves for the estimation of the percentage of separate black water collection for different values of dT, where dT refers to the time before and after black water discharge, where no grey water should be discharged in order for separation to be successful. This graph only shows the mean value.

It is evident that above about 5 households per house connections, the achievable separation percentages rapidly decrease with increasing dT. It important to note that in the SIMDEUM model there is no explicit connection between toilet flush and washing the hands thereafter. As a consequence, the likely sequence of toilet flush followed by discharge from the bathroom sink is not accounted for in the estimation of the percentage of separate black water collection. Coupling of these two events would likely decrease the percentage of separate black water collection, especially at dT>0.

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