Development of contextually adapted strategies to manage health risks related to agricultural irrigation with treated wastewater

A case study in Magabheni, South Africa

M.Sc. Thesis by Wolf Raber

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Master thesis Irrigation and Water Engineering submitted in partial fulfillment of the degree of Master of Science in International Land and Water Management at Wageningen University, the Netherlands

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Preface

First of all I would like to express my joy for having been able to visit and to do my research in such a beautiful and exciting country both from the human and natural point of view!

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Summary

In the case of limited access to fresh water resources, particularly in peri-urban areas where urban and agricultural pressure on water resources is high, municipal wastewater becomes a viable asset as a source for irrigation water. Furthermore, urban wastewater management has the objective to dispose urban drainage while avoiding negative impacts on environment and public health. Irrigation with treated wastewater is an accepted option in wastewater management in increasing more countries. However, strict official regulations on effluent quality in combination with poor institutional, financial and infrastructural settings of low income countries often restrict construction and maintenance of required infrastructure to provide effluent quality as stipulated by legislation. An effect of this paralysed situation is indirect, uncontrolled, and partly illegal use of raw sewage or poorly treated wastewater for agricultural use, which poses a risk to the environment and health of producers and consumers of crops.

The presented work gives impulses for contextual wastewater management design based on case specific requirements of agriculture and environment on water quality. The focus of the research lies on determination and evaluation of health risks for consumers of wastewater irrigated crops by Quantitative Microbial Risk Assessment (QMRA) on basis of WHO Guidelines for wastewater use in agriculture from 2006. Possible health risk reduction measures along the production chain by on-farm practice or wastewater treatment are identified. Also risk for the agronomic system and environmental pollution risk by chemical water quality in wastewater irrigation is considered on basis of FAO guidelines, drinking water quality guidelines and additional literature. Contextual specific risks are identified and evaluated for the case of a wastewater irrigation project in Magabheni, South Africa. Revealed risk factors and particular on-farm health risk reduction measures were evaluated and negotiated with farmers during the planning and implementation of the agricultural system. Based on findings from the Magabheni case maximal concentrations for selected water quality parameters of irrigation water could be concluded and hypothetical wastewater management systems are presented. Contextual developed water quality and possible treatment systems are compared with those stipulated by national legislation revealing more flexible system design in contextual wastewater management.

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Acronyms

Institutions

APHA	American Public Health Association
AWWA	American Water Works Association
DoH	Department of Health
DWAF	Department of Water Affairs and Forestry
EWS	eThekwini Water and Sanitation
FAO	Food and Agriculture Organisation
INR	Institute of Natural Resources
IWMI	International Water Management Institute
UN	United Nations
WHO	World Health Organisation
WRC	Water Research Commission

Technical data

Acronym	Meaning	Unit
BOD_5	Biochemical Oxygen Demand	[mg/L]
COD	Chemical Oxygen Demand	[mg/L]
DALY	Disability Adjusted Life Years	[-]
EC	Electronic Conductivity	[dS/m]
ET	Evapotranspiration	[mm/d]
ET_0	Reference Evapotranspiration	[mm/d]
ET_C	Evapotranspiration under Standard Conditions	[mm/d]
K_C	Crop coefficient	[-]
SAR	Sodium Absorption Ratio	[-]
SS	Suspended Solids	[mg/L]
TDS	Total Dissolved Solids	[mg/L]
TOC	Total Organic Carbon	[mg/L]
TSS	Total Suspended Solids	[mg/L]
TKN	Total Kjeldahl Nitrogen	[mg/L-N]
TN	Total Nitrogen	[mg/L-N]

Units

CFU/100 mL	Colony Forming Unit / 100 mL of water sample
Me/L	Milliequivalent per litre
MPN/100 mL	Most Probable Number / 100 mL of water sample
PFU/100 mL	Plaque Forming Units / 100 mL of water sample

1 Introduction and Background

The modern, centralized wastewater management concept origins from industrialization when spatial population density increased and claims to individual comfort advanced. Construction of streets (ground sealing), drinking water supply and household sanitation facilities raised the need to drain occurring water (storm water, supplied drinking water, wastewater) which caused a hygiene problem from urban areas. From 1850 onwards the first sewage systems in Europe channelled water untreated in rivers where eutrophication occurred due to overload of organic material and nutrients on receiving water bodies. Since the receiving environment is the eventual source of freshwater resources downstream, the environmental problem launched the development of the first wastewater treatment plants. The concept of a classical “end-of-pipe” technology; treating wastewater right before releasing effluent in surface water is still the basis of engineering thinking around the world. Organic matter and nutrients are consequently regarded as contaminants and removed under large financial and energetic effort (Lange and Otterpohl, 2000). Wastewater treatment technology has reached a high state of performance through years of development. The desired effluent water quality is a function of investment and operational costs. The level of applied wastewater treatment is institutionalized by guidelines and regulations concerning effluent quality. Initial emphasis was placed on the improvement of surface water quality while in the 1980s guidelines extended the focus on wastewater constituents that may cause adverse health effects in the population (Metcalf and Eddy, 2003).

The increasing demand for water and food of a growing world population which is living mainly in urban and periurban areas, leads to high pressure on natural water resources in terms of increased drinking- and irrigation water demand and consequent increased wastewater production (WHO, 2006; Schertenleib et al., 2002). WHO (2006) predicts that in 50 years people living in water scarce regions will account for 40% of the world population. Already today competition for limited freshwater resources leads to gradual intersectoral water transfer from water users like agriculture towards ‘primary’ urban uses of growing cities (Molle and Berkoff, 2006). There is no doubt that urban water uses require exclusively high water quality, but the agricultural sector which consumes worldwide the largest part (on average 70%, in arid countries up to 90% [http: 1]) of fresh water resources poses comparatively low quality requirements on water supply (Godfree and Godfrey, 2008). Particularly in metropolitan areas these conditions connect sanitation and water supply since subsequent use of water by the urban- and agricultural sector is possible.

In developing nations with lacking infrastructure (peri-) urban agriculture contributes to public health, assuring urban supply with fresh, affordable vegetables (Schertenleib et al., 2002). Untreated and treated wastewater use for agricultural irrigation in these countries is a reality (Scott et al., 2004). Strauss (2000) estimates approximately 10% of the world's wastewater to be used for irrigation.

If wastewater is used for agricultural irrigation in a controlled and planned manner various benefits for water management and farmers can be achieved (Asano, 1998). Potential global benefits from nutrient recycling by wastewater irrigation are less mining of limited phosphorus resources for fertilizer, reduced emission of climate gasses by energy consuming nitrogen fertilizer production and wastewater treatment (Lange and Otterpohl, 2000). Reduced pressure on fresh water resources by wastewater irrigation contributes to overcome local water shortages and competition amongst water users. Secondary benefits are decreased conveyance costs for fresh- and waste-water, reduction of fresh water facilities and limited impacts on natural water courses by water extraction.

Wastewater contaminants, particular organic and inorganic nutrients are effectively reduced or removed by ground passage of agricultural soils. This process can be considered as a form of wastewater treatment and can potentially reduce overall wastewater treatment costs while avoiding eutrophication of water bodies (Asano, 1998; Toze, 2006; Pettygrove and Asano, 1985; Jüschke, 2009; Lange and Otterpohl, 2000; WFGD, 2009; Huibers and Lier, 2005).

Potential benefits for farmers by irrigation with treated wastewater might be improvement of agricultural yield by nutrient input or reduced fertilizer costs. Wastewater could represent a cheap or cost free source of irrigation water from a year around reliable seasonal independent water source. If wastewater is the only available source of irrigation water, access to it would result in livelihood improvement for farmers (Asano, 1998; Toze, 2006; Pettygrove and Asano, 1985; Jüschke, 2009).

The use of wastewater for irrigation carries also risks due to "the quality of treated wastewater which can affect human health, potentially damage crops, plantations, the environment or contaminate groundwater." (Jüschke, 2009:12) Legal, social and economic aspects like marketability of wastewater irrigated crops are additional aspects that require further elaboration.

Considering potential benefits, use of treated wastewater in agriculture is not only an accepted concept in wastewater management (Metcalf and Eddy, 2003), but advanced to an internationally recognized paradigm. The Water Supply and Sanitation Collaborative Council from the United Nations has called in the year 2000 for an radical overhaul of conventional thinking by considering waste as a resource and closing the nutrient loop by recycling and reuse of resources in environmental sanitation (Bellagio statement) (Schertenleib et al.,

2002). This paradigm also called ecological- or sustainable sanitation is carried by a number of institutions like the Sustainable Sanitation Alliance (SuSanA).
The research at hand on wastewater management for agricultural use of treated wastewater is based on a case study in Magabheni, in eThekwini municipality, South Africa. In the following an introduction on regional background of the South Africa and the specific research location is given.

Regional background of the case study

South Africa is located at the southern tip of Africa. The climate is semiarid, with subtropical zones along the east coast with summer rainfall areas and average annual precipitation of 1200 mm. 12 % of the total land area of 1,22 million km² is considered to be cultivable due to climate-soil combinations. Agriculture contributes 3,8% to the GDP and employs 8% of the workforce. Besides of maize as major agricultural export product, sugar cane, wheat, potatoes, groundnuts, citrus fruits and grapes are widely cultivated. According to FAO, approximately 1/3 of the total population of 49 million inhabitants is vulnerable to food shortages, even though South Africa is a net food exporter [http: 2;3]. “Because of poverty, food price increases, demographic changes, energy costs, climate change and other factors, there are significant risks to sustainable food security in southern Africa. Food security is an economic and social right enshrined in the South African Constitution and is essential to achieve peace and prosperity in the region.” (Sustainable Food Security Workshop, 2009:2)
In 2005, 49% of South Africa’s population lived in urban areas. In 2015 this figure is expected to rise to 64% (Human Development Report, 2007/2008). EThekwini Metropolitan Municipality (Durban) is, with 3,5 million inhabitants, the third biggest city in the country and the largest city of the province KwaZulu-Natal. It is situated in the very east of the country bordering the Indian Ocean (see Figure 1-1). Durban has a large land area of 2,292 km² compared to other South African cities resulting in a relatively low population density. Its inhabitants are mainly (68%) black Africans, followed by Asians or Indians at 20% and Whites at 9%. The official language is English with a high level of Zulu amongst the inhabitants. The climate is mild sub-tropical with mean annual rainfall of 1000 mm and mean daily temperatures between 22° - 28℃; the topograp hy is hilly, with few flat areas [http: 3;6;7].

Figure 1-1: Province of KwaZulu-Natal in South Africa [source: http: 4].

The Department of Water Affairs and Forestry of South Africa states that South Africa's agricultural sector consumes 62% of the total water share. Urban municipal areas account for 23% of the national water use, while rural settlements use only 4% for the domestic sector. Furthermore the department predicts that due to rapid population growth the share of domestic water use will increase in a few years from the current 27% to 30% - 35% of the total national use (WFGD, 2009). In respect to the expected situation in the area around Durban, the Department predicates: "The water requirements of the KwaZulu-Natal metropolitan coastal areas in the vicinity of Durban are growing rapidly. This is a result of the current economic growth, improved water supply services, urbanization of the population and associated expansion of residential and other developments being implemented. This trend is expected to continue over the medium term as implied in planned new urban developments […] which will result in increasing water requirements from limited water resources." [http: 5]

These statements reflect a dramatic situation concerning water resources in the wider Durban area. Potential reallocation of water from agriculture use to urban use will result in a substantial shortage of water for farming in the area. Water shortage will occur particularly during the dry season from April till September where a lack of precipitation makes access to irrigation water essential for year-round cropping (Figure 1-2).

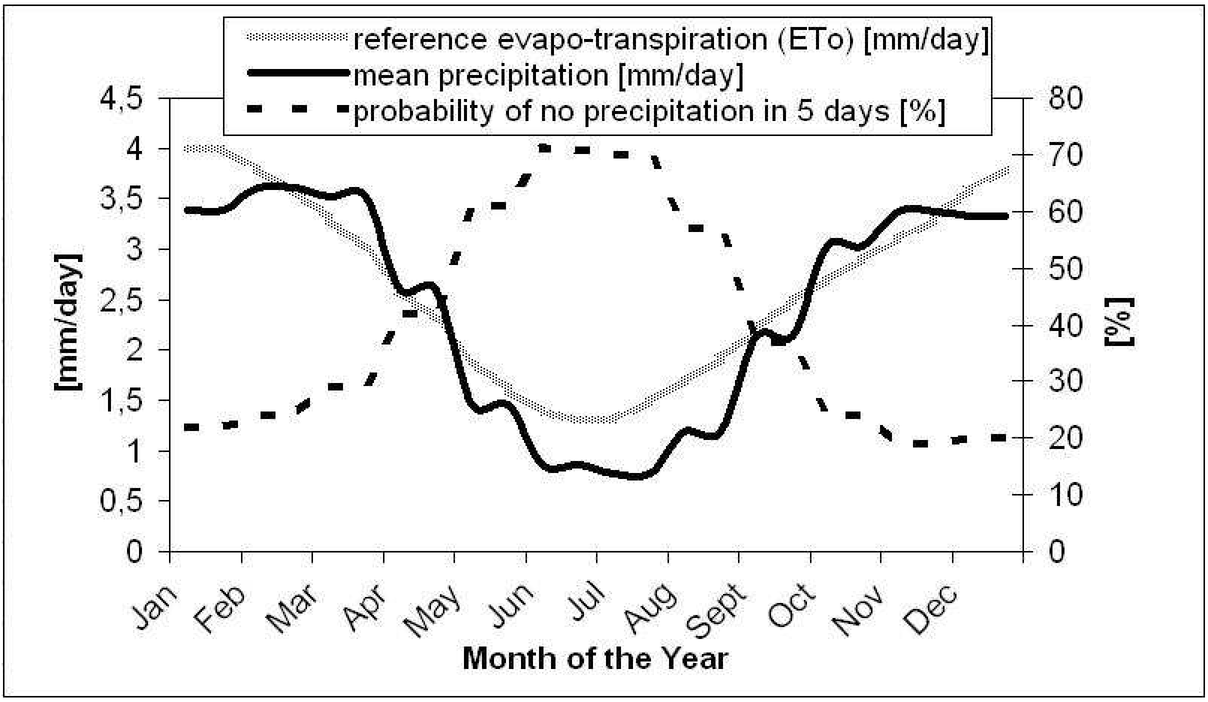

Figure 1-2: Visualized annual climatic data for Magabheni, eThekwini [source: http: 9 and New_LocClim[1]].

Considering that 26% of the urban household dwellings are characterized as informal, a huge demand exists for formal housing and accompanying water services (WFGD, 2009). Domestic water supply to new, formal housing developments will decrease the availability of freshwater for irrigated agriculture and at the same time result in the production of more municipal wastewater. South Africa has a rather high quota of population using improved water sources (88%) and improved sanitation (65%) and is aiming to further extend these services (Human Development Report, 2007/2008).

In the past regional water scarcity in South Africa was often combated by means of inter-basin water transfer. In the majority of cases this measure is inadequate due to required high financial input and the complex engineering as well as ecological and social implications (Snaddon at al., 1998). The Department of Water Affairs and Forestry of South Africa is well aware of the shortcomings of Inter-basin water transfer and emphasizes more cost efficient alternatives like effluent use in their Water for Growth and Development Framework (2009) (Figure 1-3).

When considering the significant increase of domestic wastewater production resulting from the increasing water supply in cities, the option of effluent use for irrigation to gap local water shortage is very relevant (Rooijen et al., 2005).

[1] New_LocClim, Local climate estimator, Food and Agriculture Organisation (FAO) and German Weather Service (DWD), 2005; downloaded on 8.11.2009 from: www.fao.org/nr/climpag/pub/en3_051002_en.asp

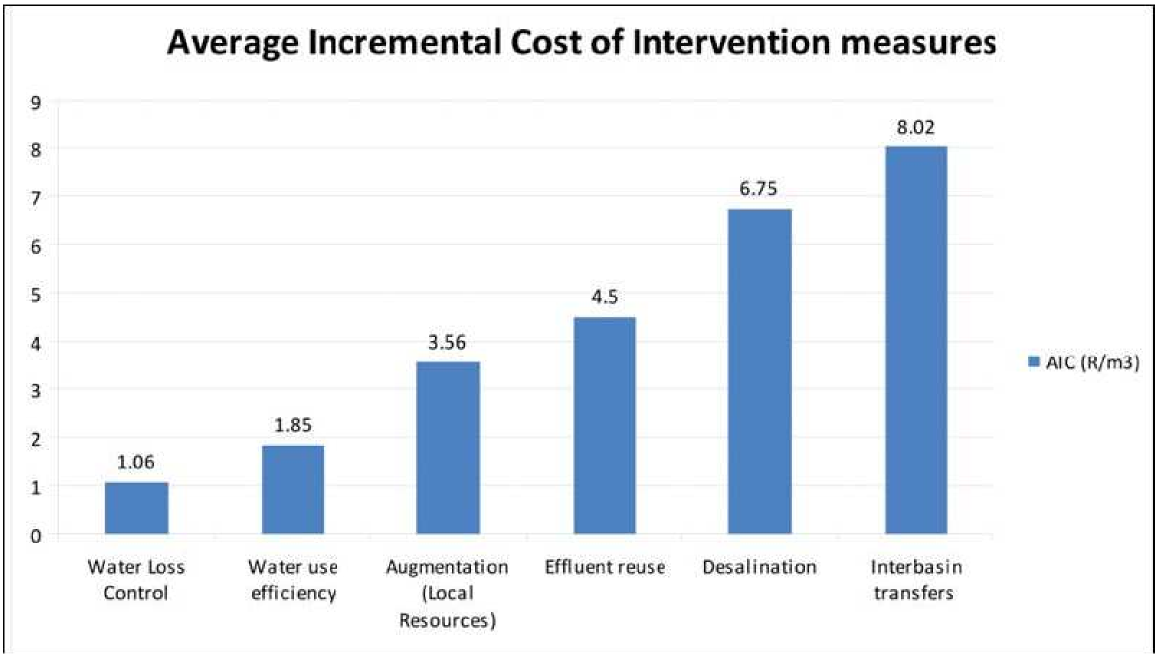

Figure 1-3: Average incremental costs for increasing water availability in South Africa in South African Rand [R] (source: WFGD, 2009:27).

The Magabheni township is located in the *Mnini* Tribal Authority in the southern part of eThekwini municipality, approximately 30 km south from Durban's urban area. The township has approximately 5000 inhabitants and is provided with a sanitary sewage system, channelling wastewater since the year 1985 into a four pond wastewater treatment system under the responsibility of eThekwini Water and Sanitation (EWS). The surrounding area is rural and supposed to be one of the poorest areas within the eThekwini municipality. In an area close to the treatment pond outfall eThekwini municipality launched in 2003 a communal agricultural project for irrigation with the pond effluent. The initial objective of the project was to solve a pollution problem of the local *Ngane* River which is used for effluent disposal. It was intended to install a post treatment step for pond effluent by agricultural irrigation with the synergic effect of creating livelihood improvement for 20 local farmers. In 2007 the irrigation project stagnated due to various reasons. In 2008 the agricultural project was modified and revitalized by eThekwini with five local farmers and a fraction of the initial 13 ha agricultural area (Figure 1-4).

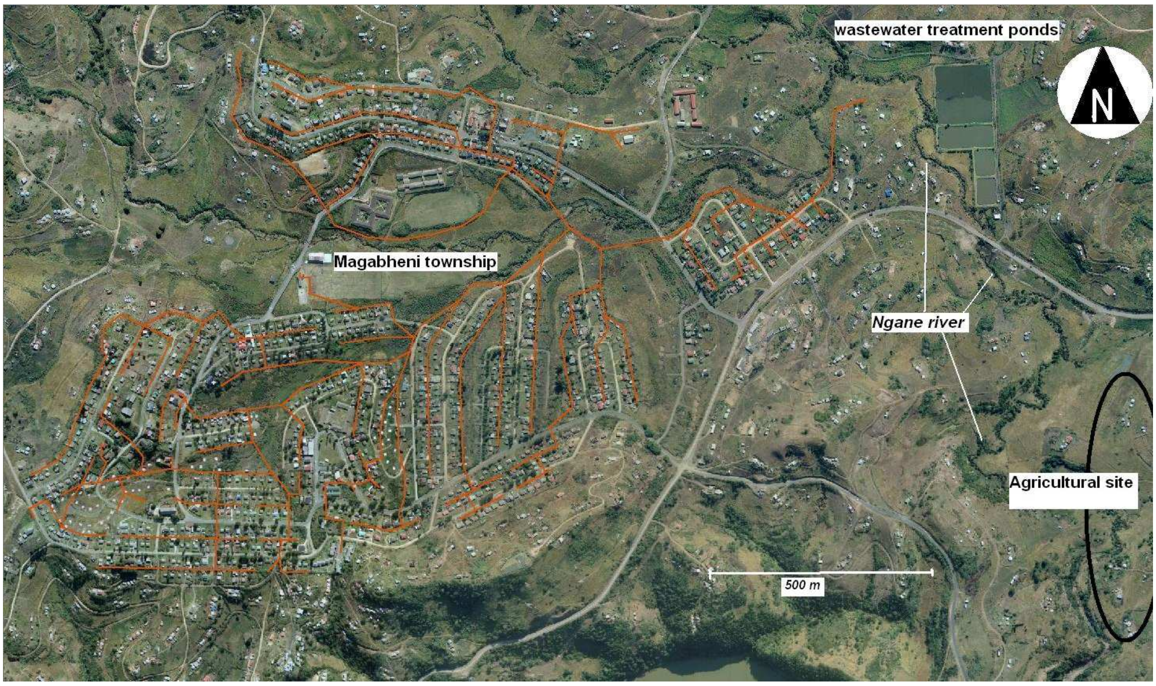

Figure 1-4: Magabheni township with sanitary sewer (red), *Ngane* river, treatment ponds and agricultural site for wastewater irrigation (GIS data from eThekwini Water and Sanitation).

1.1 Problem definition

Wastewater management for agricultural irrigation is similar to wastewater management for disposal in open water bodies organised according to guidelines and regulations. Legislation usually stipulates certain effluent quality for wastewater treatment to be permissible for agricultural use. “The acceptable concentrations are based on risk analysis, a tool that is used for deriving quality guidelines and standards.” (Sperling and Chernicharo, 2005:5) However, particular in low income countries guidelines in national legislation are often not developed in context but directly adopted from international guidelines or copied from standards of more developed countries (e.g. reuse standards of California) that might stipulate essentially pathogen-free water with low organic concentrations (Godfree and Godfrey, 2008; Sperling and Chernicharo, 2005). Hence treatment standards in low income countries become often too ambitioned for local capacities, thus purely theoretical and not implemented or enforced (Sperling and Chernicharo, 2005). Financial, operational and institutional means are insufficient to construct and maintain the required civil and logistic infrastructure to comply with and enforce effluent guidelines (Lier and Lettinga, 1999; [http: 4]). Besides of ambitioned treatment goals integration of agriculture in the wastewater management planning is often not achieved, “because many water- and wastewater agencies are established with a single-purpose function, planning by these agencies tends to be single-purpose as well” (Metcalf and Eddy, 2003:1433). Consequently, a large proportion of the wastewater in developing countries is released untreated and uncontrolled into the environment (Carr, 2005). These factors foster a paralyzed situation for controlled wastewater use and leave the role of (peri) urban agriculture for city food production and the provision of a livelihood for farmers unrecognized (Lier and Huibers, 2007). A possible reaction of farmers is indirect use of wastewater downstream of the discharge location or illegal abstraction of wastewater from the sewage system before it reaches the treatment plant in order to avoid high effluent prices resulting from sophisticated treatment technology (IWMI-RUAF, 2002). This unplanned wastewater irrigation is threatening health of farmers and consumers and creates a risk of environmental pollution.

The described dilemma calls for a wastewater management approach, away from context unspecific disposal driven wastewater management towards institutionalized integration of agriculture in an adapted and accomplishable water management concept. To achieve this goal an integrated risk management approach is needed to balance benefits of wastewater irrigation against associated risks for public health and environment in order to define contextual adapted treatment targets. Combining wastewater disposal planning with context specific treatment goals for intended effluent use may reduce treatment costs and enable planned wastewater irrigation. “The optimum water reclamation and reuse project is best achieved by integrating both: wastewater treatment and water supply needs into one plan. This integrated approach is somewhat different from planning for conventional wastewater treatment facilities where planning is done only for conveyance, treatment, and disposal of municipal wastewater.” (Metcalf and Eddy, 2003:1433)

Huibers and Lier (2005) developed the *water chain approach* in order to break down and analyze the process of an (urban) water cycle in an integrated way. The theory is grounded on the assumption that the resource water, after being extracted for a certain purpose, passes through various “ownerships” downstream till released again into natural water resources. In terms of the water chain approach agriculture might become the temporary owner of water after it had been used by primary users and before it is handed over to the environment. “The chain approach could help to constructively discuss the technical and institutional issues step by step with due attention to water quality issues and proper management at each point in the chain.” (Huibers and Lier, 2005:4) On the basis of the *water chain approach*, Huibers and Lier (2007) developed the concept of the *reverse water chain approach* which enables the institutional integration of downstream (agricultural) requirements in the design approach of water- or in this case wastewater management. “The requirements of the final users, rather than the legislation linked to a conventionally designed water chain, are taken as basis for designing the upstream water chain. Main design criteria would then include:

1) The required characteristics of the (waste) water to be used for irrigation
2) The lay-out and dimensions of the water distribution system and irrigation water storage basins
3) The location of the sewage treatment plant in relation to the agricultural field
4) The location of decentralization in view of cost reduction and the exclusion of toxic waste streams in the sewage
5) The economic affordability with respect to the required infrastructure and the costs per m^3 of treated sewage
6) The avoidance of mixing black waters (toilet wastes) with large amounts of relatively clean waters, creating a huge pool of infectious water.

In such an approach, the type and functionality of the wastewater treatment system is determined by the farmer's need rather than by governmental legislation for wastewater discharge." (Lier and Huibers, 2007:3-4)

The research at hand is contributing to a design approach for wastewater management for agricultural reuse from the reverse water chain perspective. A focus is put on down stream water quality requirements which are developed in a contextual adapted manner as suggested in Huibers and Raschid-Sally (2005).

Next to socio-cultural, institutional and economic aspects health risks for farmers and consumers is the major concern associated with irrigation of eatable crops with municipal wastewater (Asano, 1998; Godfree and Godfrey, 2008). Sustaining soil quality and agricultural production by providing chemical acceptable water quality is a substantial demand of farmers (Godfree and Godfrey, 2008). Environment as the ultimate receiver of water supplied afore to agriculture is posing qualitative demands on water supplied by the upstream water chain to avoid environmental degradation. This research is based on risk assessment with a focus on health risks for consumers of agricultural products performed by Quantitative Microbial Risk Assessment. Risks for the agronomic system by FAO guidelines and literature study and risks for environmental contamination by literature study are also evaluated. Health risks for farmers receive only minor attention since it is controllable with simple protection measures taken by farmers as presented in the case study.

For development of contextual water quality demands of a specific agriculture site towards wastewater management the case study of the community farming project in Magabheni township, in the eThekwini municipality in South Africa is used. The research investigates health, environmental and agronomic risks origin from irrigation with given wastewater treatment pond effluent. On the basis of gathered data, assumptions of required irrigation water quality and consequent possible wastewater management systems for the agricultural setting found in Magabheni community gardens are concluded and compared with national legislation.

1.2 Outline of the report

After the introduction which includes background information, area of study and problem definition; research objectives inclusive main and sub- research questions are presented. Conceptual design, methods used to collect and analyse data and the scale of the study are introduced in the subsequent chapters. The rest of this report is organised as follows: Chapter 5 presents results of the research. Results are subdivided into physical description of Magabheni, literature study investigating on typical wastewater characteristics and attached health, agronomic and environmental risk by wastewater irrigation. The literature study results in the construction of a QMRA and a presentation of South African legislation on wastewater irrigation. The third part of results encompasses the assessment of mentioned risks for Magabheni and presentation of results of a workshop with the community of local farmers. During the workshop on-farm measures for personal health protection and health risk reduction for consumers were developed.

In the conclusion (Chapter 6), findings from risk evaluations are compiled and water quality requirements for irrigation water are developed. Hypothetic wastewater management systems are developed and compared with those stipulated by national guidelines.

Chapter 7 presents discussion and recommendations followed by the bibliography and appendix. In the appendix a detailed description of the cases study is presented including project history, results from livelihood analysis of Magabheni farmers and the surrounding community as well as the followed design and implementation approach of the agricultural site.

2 Research Objective

The general objective of the research is to study and explore the potential contribution of contextual risk assessment for wastewater management system design from the downstream perspective according to the reverse water chain approach.

In order to realize this objective, the following specific objectives were devised:

- Find methods to determine context specific health risk for crop consumers, potential risks for the agronomic system and environmental pollution risks attached to wastewater irrigation;
- Determine the agricultural system and physical features for the case of Magabheni community gardens;
- Compare possible wastewater management systems with wastewater management as stipulated by national legislation.

2.1 Main Research Question

What water quality requirements does the wastewater irrigation project in Magabheni, South Africa pose on the wastewater management system on the basis of contextual assessment of health risk for consumers and evaluation of potential risks for the agronomic system and environmental pollution? How does a potential wastewater treatment system look like in comparison to those systems stipulated by national legislation?

2.2 Sub questions

- How is the physical appearance of the wastewater irrigation site in Magabheni?
- What kind of agricultural management structures are apparent in Magabheni?
- How is typical raw wastewater quality?
- What health risks are present for consumers of wastewater irrigated crops and how can these be measured?
- What are possible intervention strategies for health risks for consumers?
- What water quality is required to avoid adverse effects on the agronomic system and environmental contamination by irrigation with treated municipal wastewater?
- What are the irrigation water quality requirements for irrigation in Magabheni corresponding to health, agronomic and environmental risks?
- What kind of wastewater management systems for wastewater irrigation does national legislation stipulate?

3 Concepts

The research at hand uses certain concepts and definitions to analyse and discuss the requirements agriculture poses to a wastewater management system. These concepts and definitions are introduced and clarified in the following.

3.1 Household livelihood approach (only used in Appendix)

The way farmers are using wastewater depends mainly of the state of their livelihood assets as a main driving factor behind any action (Moser, 1998; Buechler, 2004). Besides of farmers objectives and capacity to adopt farming practice also behaviour (preferences and capacity to purchase and consumption patterns) of local customers of agricultural products are dependent of their household livelihood context and assets. The research is based on investigations on sustainable livelihood of farmers and community households in order to estimate the long term behaviour of the agricultural system as input parameter for contextual adapted risk evaluation.

Chambers and Conway (1992) define sustainable livelihood as follows:

"A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks, maintain or enhance its capabilities and assets, while not undermining the natural resource base." (Buechler, 2004:30)

In Figure 3-1 one can see the basic sustainable livelihood framework, developed by Chambers and Conway (1992). In this research exclusively livelihood assets are used for investigation on farmers and the community.

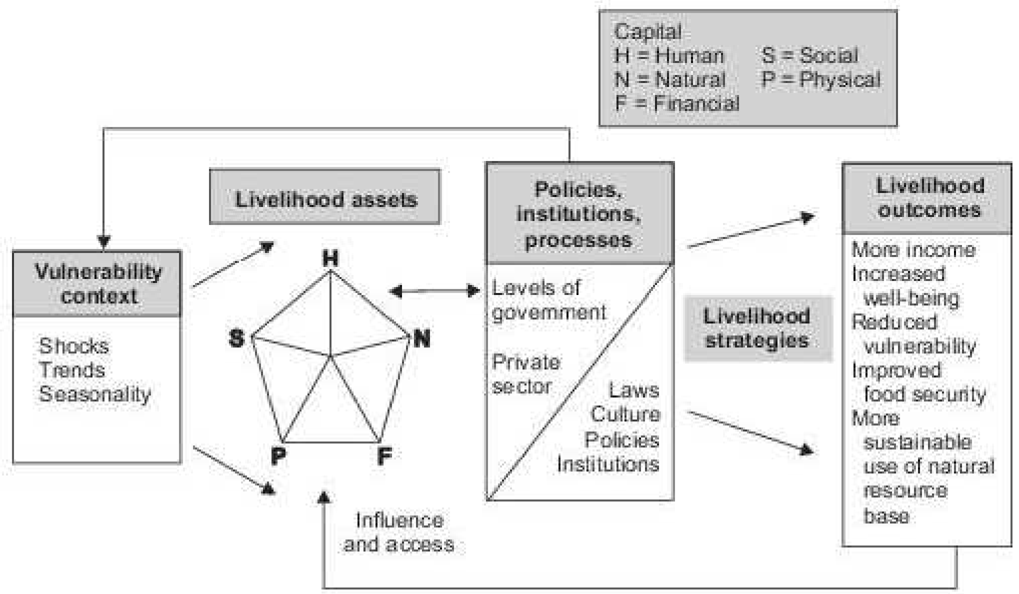

Figure 3-1: Sustainable Livelihood Framework [Source: DFID, 2003] (Buechler, 2004:31).

The livelihoods framework views poor households as being dependent upon a diversity of strategies in order to face urban poverty. These strategies are based on a set of household assets: natural capital (land and water); financial capital; physical capital (houses, equipment, animals, seeds); human capital (in terms of both labour power and capacity, or skill); and social capital (networks of trust between different social groups). The deployment of assets also depends on external influences such as dealing with regulations, policies, urban authorities and local marketing practices (Buechler, 2004).

3.2 User

In the research the focus lies on users of wastewater for agricultural purposes which are defined as farmers or farmer households that manage wastewater for irrigation.

3.3 Wastewater

Review of various wastewater typologies in literature leads in Hoek (2004) to a common wastewater typology for urban wastewater. This research will discuss exclusively municipal (domestic) wastewater from water born sewage systems, consisting of blackwater (excreta, urine and associated sludge) and greywater (kitchen and bathroom wastewater) (Hoek, 2004:14).

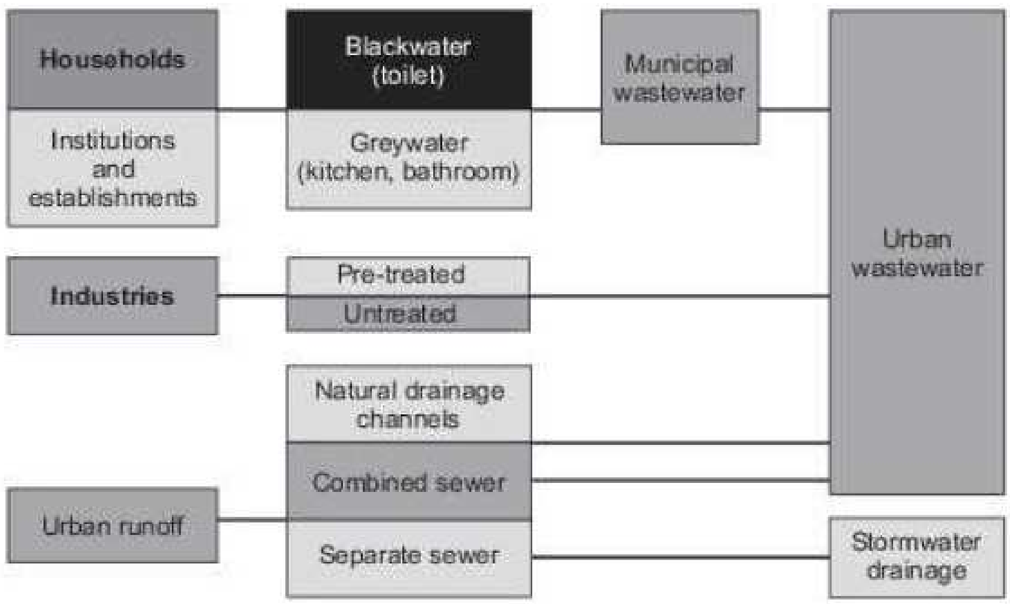

Figure 3-2: Urban wastewater composition (source: Hoek, 2004:14).

3.4 Effluent

Effluent water is defined as “liquid discharged from a processing step” (Metcalf and Eddy, 2003:4) and represents the discharge of a wastewater treatment plant.

3.5 Wastewater treatment

Wastewater treatment is defined as technical processing of wastewater. Different degrees of treatment or treatment steps can be distinguished:

- With primary treatment only debris and solids are removed through suspension.
- Secondary treatment decreases the COD (chemical oxygen demand) of the wastewater, thus also reducing pathogen concentrations.
- With tertiary treatment nutrients and micro-pollutants can be removed (Metcalf and Eddy, 2003).

The clear classification of treatment methods in above mentioned treatment steps is often not possible. The classification intends to give a rough categorization to analyze treatment systems.

3.6 Wastewater management

Wastewater management describes the implementation and operation of collection, treatment, use and disposal systems for wastewater.

3.7 Wastewater use

What is called ‘wastewater use’ in this document is in literature often referred to as ‘wastewater reuse’. This terminology has a notion of upstream planning focusing on singular use only and does fit to the downstream perspective taken in this research. In addition the term wastewater itself implies already to be the product of a primary use and the combination with the term reuse is a duplication of meaning. Consequently I will stick to the terminology ‘use’ of wastewater.

Wastewater use describes the “beneficial use of reclaimed (treated) wastewater” (Hoek, 2004:16). Wastewater use in this document will only be discussed in terms of agricultural use of treated wastewater. Wastewater use is conceptualized as direct use of treated wastewater. The definition is valid for effluent use where control exists over the conveyance of the wastewater from the point of discharge from a treatment works to a place where it is used for irrigation (Hoek, 2004).

3.8 Health risks for consumers

Health risks are the measure of the probability to experience adverse health effects by ingesting crops contaminated with microbial pathogens (hazards) (Davis and Vornwell, 2001). Health risks are quantified by the Quantitative Microbial Risk Assessment (QMRA) in additional disease burden for individuals by exposure to a certain pathogen.

3.9 Risks for the agronomic system

Risk for the agronomic system describes potential adverse effects on crop yield by chemical water constituents and their accumulation in the soil profile. The risk itself will not be quantified but permissible chemical concentrations to avoid adverse effects on crop yield will be retrieved from guidelines and related literature.

3.10 Risks for environmental pollution

Risk for environmental pollution describes potential adverse effects by chemical stressors on any ecological component, which might be individuals, communities, or ecosystem (Kester, et al. 1994). In this document potential adverse ecological effects are not being quantified. Presence or not presence of risks for environmental contamination by leaching of substances into groundwater is going to be estimated on the basis of guidelines of permissible substances in drinking water and degradation rates of substances in soil. Other environmental aspects are not considered given the limited scope of the study.

3.11 Quantitative Microbial Risk Assessment (QMRA)

Haas et al. (1999) defines risks assessment as a “qualitative or quantitative characterization and estimation of potential adverse health effects associated with exposure of individuals or populations to hazards.” (Haas et al., 1999:86) The WHO (2006) further defines QMRA as a tool to ”estimate the risk to human health by predicting infection or illness rates to given densities of particular pathogens, measured or estimated rates of ingestion and appropriate dose-response models for the exposed population. QMRA provides a technique for estimating the risks from a specific pathogen associated with a specific exposure pathway” (WHO, 2006:14)

4 Research methodology

The research at hand is composed of two parts. In the first part a literature study is carried out on potential health, environmental and agronomic risks evolving from wastewater irrigation and on QMRA as a tool to quantify health risks for consumers. In the second part of the research insights on risk evaluation are applied in a case study. Input data for risk evaluation of the Magabheni wastewater irrigation site are retrieved by various means and findings are used to conclude on required effluent quality for the specific case.

Investigations on risks attached to agricultural irrigation are focused on microbial health risks for consumers of agricultural products consumed raw. A QMRA is carried out on the basis of two pathogenic species (*Rotavirus* and *Campylobacter*) to quantify attached health risks and identify health risk reduction measures. Health risks for farmers by irrigation with treated wastewater receive only minor attention in the risk assessment, but personal health protection measures are developed in a participative manner. Risks for the agronomic system and risk of environmental pollution are identified, but only quantified roughly on basis of the main wastewater constituents of concern.

The field study focuses on the area of Magabheni community gardens of one hectare managed by 5 farmers. Investigations on site were carried out from June till August 2009. Twenty household surrounding the agricultural site were interviewed on their household assets and vegetable consumption patterns.

4.1 Data collection

Primary data sources are data that are not in previous existence but directly acquired from field. Primary data can be obtained through interviews, survey questionnaires and field observations. Secondary data are usually sourced from literature, official documents, project reports as well as relevant websites.

In the literature study secondary data was collected and reviewed. Technical handbooks and scientific journal articles on wastewater treatment and use were reviewed to gain insights on typical wastewater quality and methods of wastewater irrigation, including attached risks for environmental contamination. Literature was recommended from Professor C. Buckley, Pollution Research Group of the University of KwaZulu-Natal; and found by search in the library catalogue of the Technical University of Berlin and Wageningen University as well as databases like Scopus, Science Direct, Google and Google scholar. The following key words were used to start the search for desired literature: *wastewater treatment, wastewater reuse, wastewater irrigation, wastewater reclamation, land treatment of wastewater, Abwasser* and *landwirtschaftliche Bewässerung mit Abwasser.* As literature research continued more specific terms were used. To find literature on potential adverse effects of irrigation water quality on the agronomic system the database of the FAO was searched with the following key words: *water quality for irrigation* and *irrigation with treated wastewater.* Secondary data collection on health risk for consumers of agricultural products and QMRA started with the WHO (2006) Guidelines: Wastewater use in agriculture. Literature recommendations from S. Jackson, head of analytical laboratories of EWS, from A.J. Hamilton from the University of Melbourne and Professor D. Mara from Leeds University (who also provided a Microsoft Excel based dose response model), were used for further research on QMRA. From initially collected literature additional literature review was carried out on specific topics of QMRA in the databases Scopus and Google as well as on the WHO database, mainly searching for specific scientific articles referred to in prior retrieved literature.

In the case study part of the research both primary and secondary data were collected.
Primary data on farmer objectives and assets as well as household assets and vegetable consumption patterns of the nearby community were collected by semi structured interviews with one or more persons of each household and individual farmers as presented in Appendix 9.5.
Interviews with household were in-depth interviews as described in Kumar (2005). They focused on household assets and objectives according to the Household Livelihood Security Assessment (HLSA) as suggested in Frankenberg et al. (2004). “Information on household demography, assets and resources, months of self-provisioning, proportion of income spent on food, times of seasonal stress and specific coping strategies are captured.“ (Frankenberg et al., 2004:23) Vegetable consumption patterns of households were captured with a brief questionnaire during in depth interviews. The questionnaire was composed of closed-end questions (Kumar, 2005), asking for a selection of vegetables if consumed at all, and if so if raw or cooked, and if raw the open-end question was posed: how often consumed and in which dish. The selection of vegetables was prior composed. In order to find all possible locally consumed vegetables, observations on markets and interviews with agricultural trainers from Newlands Kwa-Mashu agricultural training centre were conducted. Each household interview was performed in approximately one hour of time with a Zulu interpreter. Farm practise on the field was observed occasionally by non-participant observation. For the development of health protection measures and on-farm health risk reduction measures, farm practice was studied by participant observation during a two days workshop (Kumar, 2005). Further primary data was collected by semi structured interviews with municipal planners and consultancy companies contracted for project facilitation and implementation. Various meetings of representatives of the municipality and facilitating company were visited and used for participant observations. Old and current project reports, proposals and

analytical data of pond effluent by EWS were accessible for secondary data review due to assistance in project planning and implementation of the Magabheni wastewater irrigation project. To verify historical secondary data, primary data was retrieved by few spot tests on wastewater flow rates entering the Magabheni wastewater treatment pond system with a bucket of defined volume and stop watch. The depth of Magabheni wastewater treatment pond system was measured by few improvised bathymetric spot tests with a sinker on a string and a measuring tape. Legislative documents relevant for wastewater irrigation were found in former project proposals, project documents and online search in the Database of the Department of Water Affairs and Forestry (DWAF) of South Africa. Secondary information on the project area was added by data provided by EWS in form of Geographical Information System layers.

Retrieved information was recorded in a field diary and partly processed in Microsoft Excel.

5 Results

5.1 Description of the Magabheni site

In the following wastewater management in Magabheni will be characterised and physical and climatologic conditions of the agricultural site will be described.

5.1.1 Wastewater management

In 1985 a four pond treatment system was constructed at Magabheni to treat the wastewater from the Magabheni Township. Effluent was till date disposed in the *Ngane* River and is now partly used for agricultural irrigation of the Magabheni community gardens. Design dimensions of the lined pond system (Dept. of Development Aid, 1985) are presented in Table 5-1. The treatment ponds are not operated and maintained by a local operator. According to the responsible supervisor of the Kingsburg wastewater treatment plant (in approx. 15 km distance); once a week a worker from Kingsburg inspects the ponds. The ponds have never been desludged and maintenance is rarely necessary. Flow rates are estimated to be 250 m^3/day based on the potable water supply to the community, though the exact amount of connected households and length of the canalisation system are unknown due to data loss during administrative transformation after apartheid. The only fact certainly known is that the inflow is 100% domestic and that a sanitary sewer system is in place, conveying sewer without stormwater runoff (pers. E-mail exchange Mr. Dhukan, superintendent Kingsburgh wastewater treatment works, Aug. 2009).
Since the ponds have never been desludged few spot-test measurements were performed by the author on pond depth to gain a better approximation of pond volume and consequent hydraulic retention time of wastewater. This was done with an improvised measuring device with which it was possible to measure the depth approximately two meters away from each corner of each treatment pond. The depth was less (~1/2) than in design data specified, but corners are also expected to be particularly prone to accumulate sludge. For this reason the mean of design volume and calculated volume is used as a realistic estimation of pond volume. With the pond volumes and maximum and minimum seasonal flow rates (Figure 5-2) theoretical hydraulic detention time can be calculated for each pond. Pond volume is divided by flow rate to calculate the hydraulic detention time of the theoretical ideal plug-flow reactors (Metcalf and Eddy, 2003). The results of measurements, calculations and functions of each pond are presented in Table 5-1.

Table 5-1: Magabheni treatment pond properties retrieved from historical documentation Dept. of Development Aid (1985) and spot tests.

	Function	Area [m²]	Design volume [m³]	Estimated volume [m³]	Estimated hydraulic retention time [day]
Pond 1	Anaerobic pond	17550	28080	21255	70 - 79
Pond 2	Facultative pond	6500	10400	7775	25 - 29
Pond 3	First Maturation pond	2820	4512	3266	11 - 12
Pond 4	Second Maturation pond	2820	4512	3316	11 - 12

5.1.2 Wastewater quantity

The exact flow rates of wastewater coming from the Magabheni Township and being treated at the Magabheni treatment pond system is unknown since there are no measuring devices in place. In a folder from the former irrigation project manager with documents of the Magabheni wastewater irrigation project, a document was found showing flow rate measurements of three days, which was not clearly labelled but is expected to be taken at the Magabheni treatment ponds. Five spot test flow rate measurements on the 5th and 17th of August 2009 with a bucket of defined volume and a stopwatch show a good correlation with the given data (Figure 5-1). The given data of one day full measurement and two half day measurements will be used to calculate an average flow rate and daily inflow.

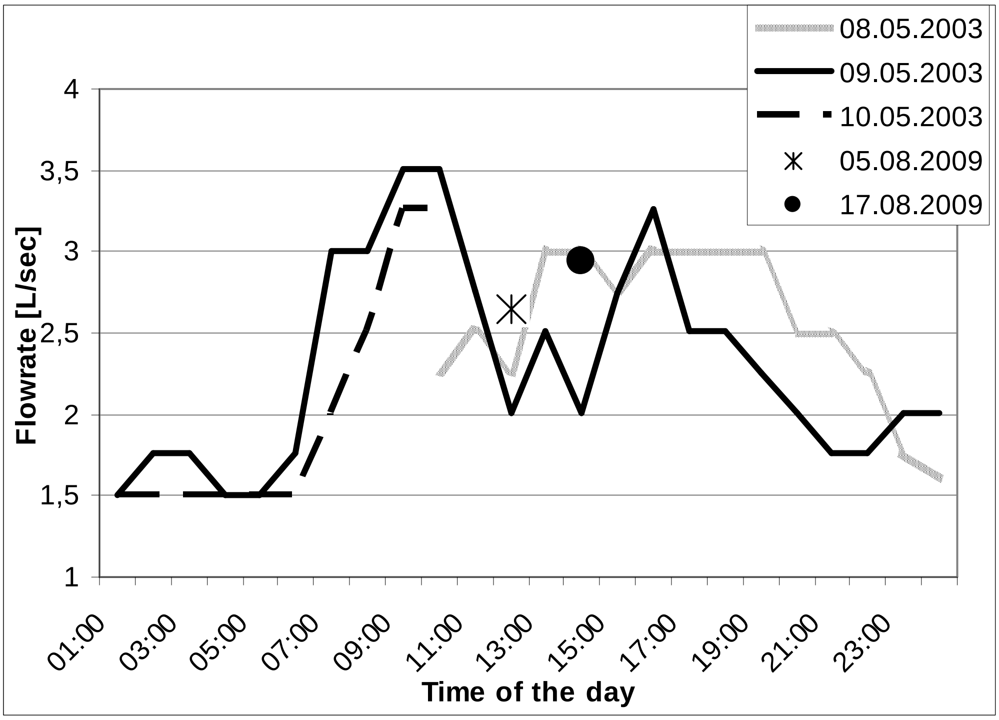

Figure 5-1: Sewage flow rate at Magabheni treatment pond inflow from May 2003 and spot test measured in August 2009 (source: unidentified document and spot test averages).

The average of available data presented in the figure above results in a flow rate of approximately 200 m^3/day (= 2,3 L/sec; 8,3 m^3/h). Since the conveyance system is a sewer canalisation, the flow rate of raw sewer is not expected to change considerably over seasons.

The water supply model in Magabheni (explained in Box 1) and extremely low water consumption rates (<25 L/person per day) recorded in rural areas [http: 11] allow the assumption that no significant change in seasonal consumption habits have to be expected. Analysis of the Magabheni Township with a Geographical Information System using layers provided by eThekwini municipality with approximate location of sewage pipes and areal photographs with potentially connected households allows the conclusion that approximately 770 households are connected to the treatment ponds. Considering the calculated 200 m^3/day raw sewage leaves the conclusion that each household disposes approximately 260 L wastewater per day in the sewage system. Regarding water consumption habits this value seems realistic.

Box 1: Water supply policy and system in Magabheni (source: [http: 12]).

In 2003 the National Cabinet adopted a Strategic Framework for Water Services which provides a policy for water services and sets a framework for its implementation over the next 10 years. According to this legislation all households are supposed to have access to free basic water supply by 2008 and access to basic sanitation by 2010. The free basic service for water supply stipulates that all customers receive the first 6 m^3 per month free of charge, with various rising block tariff and fixed charge structures for those customers receiving a full or semi-pressured supply. All water supplied via standpipes is free of charge. According to the degree of urbanization different supply models are offered to customers. In Magabheni either a roof tank or a ground tank is filled daily with 200 liters (equivalent to the 6 000 L free per Month) via a semi pressured supply system. Are these 200 liters finished, more water can be withdrawn but needs to be paid. In this definition a customer is one household and not one person.

Other than the pond inflow, the outflow will be influenced by evaporation and precipitation.

Seasonal adjustment of flow rates at pond outlet requires to link precipitation and evaporation data. Evaporation data for the region are not recorded or accessible and an approximation by using evapotranspiration data is required. FAO (1998) recommends a modification of the $K_{c\ ini}$ value at sowing phase if heavy rain is occurring and water is logged. During sowing phase no transpiration is happening since the crop is not yet developed. If heavy rain is occurring, water stands on the surface during the first day and for this case FAO (1998) recommends to use a K_c value of about 1,1 to describe evaporation. The author is aware that evaporation from an open water body is different than evaporation from a very wet soil, though the calculation is going to be performed according to the equation below to give an approximation of occurring effluent. The calculated seasonal dynamic of pond outflow is presented in Figure 5-2.

Equation 1

$$\Delta Q = (P - ET_0 \cdot K_{c\_adj}) \cdot A_{ponds}$$

With:

ΔQ	[m³/day]	= change in flow rate
P	[m/day]	= precipitation
ET_0	[m/day]	= evapotranspiration
K_{c_adj}	[-]	= K_c for sowing season with heavy rain (1,1)
A_{ponds}	[m²]	= total surface of treatment ponds (29690 m²)

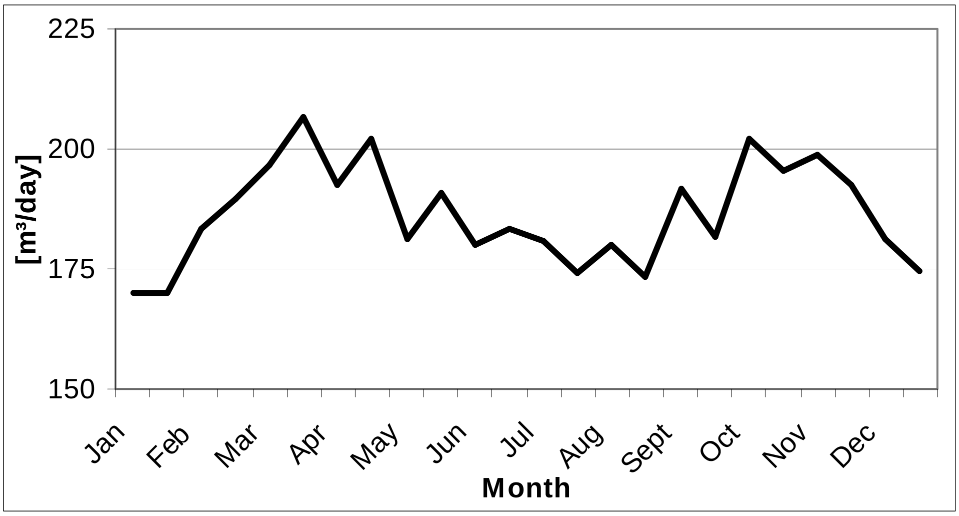

Figure 5-2: Seasonal outflow of Magabheni Pond System under consideration of precipitation and evaporation.

5.1.3 Chemical wastewater quality

On the basis of monthly sampling and measurements[2] of water chemical parameters in the Magabheni pond system by the *eThekwini Water and Sanitation: Scientific Services* from November 1999 till 2009 present effluent quality can be estimated. Measurements of the raw sewage quality are not available and have to be estimated with data given in Metcalf and Eddy (2003) on typical raw wastewater quality. To evaluate risks arising from irrigation with effluent, raw wastewater quality is only of secondary interest.

Free ammonia [mg/L-N] and COD [mg/L] are the only parameters measured in all four ponds. The values for ammonia show a clear seasonal variance in all ponds. As presented in Figure 5-3, ammonia concentrations are usually low in the hot, rainy summer season around January and at its maximum in the dry, colder winter season. COD does not show these seasonal variations.

[2] Analytics according to standard methods from AWWA / APHA Standard Methods (Pers. E-Mail contact S. Jackson, EWS Jan. 2010)

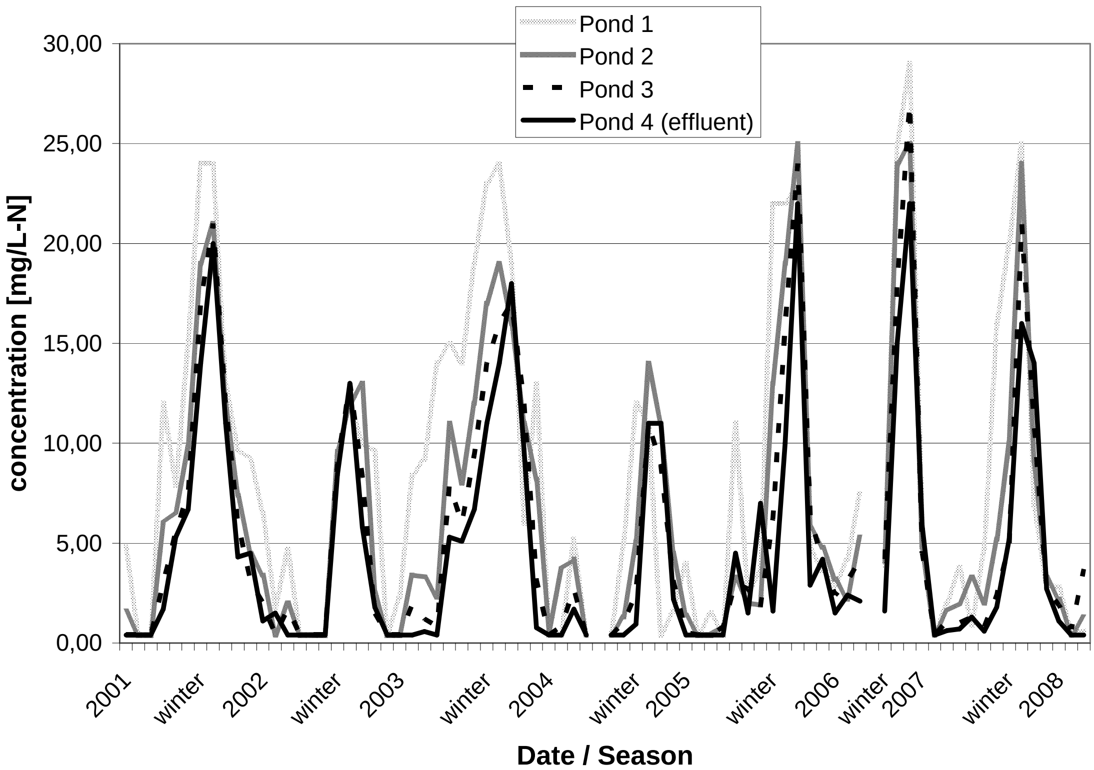

Figure 5-3: Seasonal variation of free ammonia in all four Magabheni wastewater treatment ponds.

Because of presented seasonal variations of water quality and expected need for irrigation in the dry winter season (Figure 5-4), only chemical water quality parameters of the winter season (May – September) are considered.

Measurements of water quality (other then COD and ammonia) were only performed for the outflow (Pond 4) of the Magabheni wastewater treatment ponds.

Chemical parameters of the Magabheni pond system effluent, measured[3] monthly by *eThekwini Water and Sanitation: Scientific Services* from November 1999 till April 2009 can be reviewed in Table 5-2. Displayed values are averages of all available concentrations between May and September as justified above.

Table 5-2: Average chemical effluent quality in the irrigation season (May – September) of the Magabheni pond system on basis of analytical data from EWS.

COD [mg/l]	Suspended solids [mg/L]	pH	Ammonia [mg/L –N]	Nitrate [mg/L - N]	Conductivity [dS/m]
84	41	7-10	7	1,3	0,6

Due to redesign of the wastewater irrigation project five samples from the period January till May 2009 of the pond outflow were analysed on a larger array of chemical parameters (intensive survey). The measurements are not in the chosen target season but their average values (Table 5-3) will be used as approximation of year around water quality. For further

[3] Analytics according to standard methods from AWWA / APHA Standard Methods (Pers. E-Mail contact S. Jackson, EWS, Jan. 2010)

evaluation the respectively higher value of long term survey and intensive survey will be used. For the calculation of the sodium adsorption ratio (SAR) only data from the intensive survey are used, since SAR is based on the relation of parameters to each other which should not origin from two different datasets.

Table 5-3: Average effluent concentrations from intensive analytical survey performed by EWS.

Parameter	Value
Ammonia (free) [mg/L –N]	1
Calcium [mg/L]	21[b]
Chloride [mg/L]	77[d]
COD [mg/L]	140
Conductivity [dS/m]	0,5
Magnesium [mg/L]	12[c]
Nitrate + Nitrite [mg/L –N]	0,8
Ortho phosphate [mg/L –P]	0,7
pH [-]	8 - 9,6
Residual chlorine [mg/L]	0,3
Sodium [mg/L]	62[a]
Sulphate [mg/L]	31
Suspended solids [mg/L]	48
TKN [mg/L – N]	1,4
Total Nitrogen [mg/L –N]	1,8
Total Phosphate [mg/L –P]	1,0
Turbitity [NTU]	83

[a] Na^+ = 3,48 me/L
[b] Ca^{2+} = 1,10 me/L
[c] Mg^{2+} = 1,15 me/L
[d] Cl^- = 2,17 me/L

Besides electronic conductivity, the sodium content in irrigation water is relevant for deterioration of soil (formation of crusts leading to water logging and reduced soil permeability). The unitless SAR quantifies the proportion of sodium to magnesium and calcium and can be calculated with Equation 2 (Metcalf and Eddy, 2003; Ayers and Westcot, 1985). In the equation: Na, Ca and Mg (sodium-, calcium-, and magnesium-ions) are inserted in milliequivalent per litre (me/L).

Equation 2

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

The SAR for the values shown in Table 5-3 is 3,3.

The given basis of chemical water parameters can be extended by Table 5-8 suggesting typical mineral increase by domestic water use based on consumption patterns of 460 L/capita and day. Even though the consumption patterns regarding amount and use of domestic water are assumingly different for the Magabheni case, the suggested data correlate sufficient with the sampled ones (Table 5-4). For later reference, the upper values of suggested concentrations will be used. Low per capita water consumption, and potential water losses due to evaporation in the pond system result in high concentrations of mineral constituents in the pond effluent.

Table 5-4: Comparing measured minerals in pond effluent with data suggested by Metcalf and Eddy (2003).

Constituent	Measured in pond effluent [mg/L]	Suggested by Metcalf and Eddy (2003) [mg/L]
Chloride	77	20 – 50
Sulphate	31	15 – 30
Calcium	21	6 – 16
Sodium	62	40 – 70
Magnesium	12	4 – 10

The given data are estimations for raw wastewater. Metcalf and Eddy (2003) argue that mineral concentrations are not altered significantly by the wastewater treatment process and consequently the same concentrations can be expected also for effluent. For the case of Magabheni this assumption might not count for ions, which are part of the calcite and carbonic acid equilibrium. As later discussed, biological processes in wastewater treatment ponds might alter concentrations significantly.

5.1.4 Soil and aquifers

In 2003 a soil scientist from the department of Agriculture and Environmental Affairs analysed the soils of the Magabheni irrigation site. He reported that “the texture of the topsoil was estimated (field test) to be 25-40 % clay, with a substantial increase in clay in the subsoil. The in-field permeability test indicated that the permeability of the upper subsoil is slightly restricted. […] Soil and water samples taken on 18 July 2003, and analysed by Umgeni Water, showed very low levels of any of the major potential pollutants. In the light of these analyses and the low volumes of effluent to be used for irrigation, there would appear to be a low potential for the long term build up of any of the potential pollutants. The restricted internal drainage further minimizes the potential of any pollutants being leached out into the ground water.” (Liengme, 2003:1) According to Business Plan for Magabheni from 2003 the agricultural site falls under bioresource unit (BRU) Ya12 which is an agricultural, geographical cadastral system for the province KwaZulu-Natal (INR, 2003). According to the system the soil has over 35% clay in the A horizon which is 500-800 mm deep. With a slope of 2-5% the soil is suitable for irrigation (INR, 2003; Camp, 1995).

The aquifer located underneath the Magabheni Township and agricultural site is not used for drinking water production (Umgeni Water, 1998).

5.1.5 Precipitation and evapotranspiration

With the help of the climate modulation program *New_LocClim*[4] local climatic conditions of the Magabheni community gardens site (coordinates: Latitude: 30° 10' South; Longitude: 30°47' East) including the potential evapo-transpir ation can be estimated. Potential evapo-transpiration is similar to reference evapo-transpiration but calculated with a slightly different method. In this document is only an estimation of the evapo-transpiratioin needed and calculated potential evapo-transpiration will be regarded as a sufficiently good approximation (pers. comm.. H. Boesveld, Irrigation and Water Engineering Group, Wageningen University, Nov. 2009).

Table 5-5: Reference evapotranspiration (ET_0) ≈ potential evapo-transpiration in half month sets calculated with New_LocClim[4].

Month [two weeks]	Jan I	Jan II	Feb I	Feb II	Mar I	Mar II	Apr I	Apr II	May I	May II	Jun I	Jun II
ET_0 [mm/day]	4	4	3,8	3,6	3,3	3	2,6	2,3	1,9	1,6	1,4	1,3
Month [two weeks]	Jul I	Jul II	Aug I	Aug II	Sept I	Sept II	Oct I	Oct II	Nov I	Nov II	Dec I	Dec II
ET_0 [mm/day]	1,3	1,5	1,7	1,9	2,2	2,5	2,7	2,9	3,1	3,3	3,6	3,8

With the South African Rain Atlas [http: 9] the mean monthly rainfall, according statistical standard derivation and the probability of no rainfall in 5 days in a row can be simulate.

Table 5-6: Simulated mean monthly rainfall, monthly standard derivation and average probability of no rainfall in 5 days [9].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean rainfall [mm/month]	105	101	109	78	45	26	37	37	64	94	101	103
Standard derivation [mm/month]	66	67	74	64	47	33	38	38	49	60	61	62
Probability of no rain in 5 days [%]	22	24	29	42	61	71	70	57	37	24	19	20

By visualizing presented local climate data in Figure 5-4 the dry winter month can be identified as irrigation period. From May till September evapo-transpiration is higher than precipitation. In this period average precipitation is low and rainfall events are less than in other month. The probability of five consecutive dry day is up to 70%. In the driest month (June) the probability for 10 days without rain is approximately 50% and 15 days 38% accordingly [http: 9]. Even though evapotranspiration is also comparably low irrigation is required for successful vegetable farming.

[4] New_LocClim, Local climate estimator, Food and Agriculture Organisation (FAO) and German Weather Service (DWD), 2005; downloaded on 8.11.2009 from: www.fao.org/nr/climpag/pub/en3_051002_en.asp

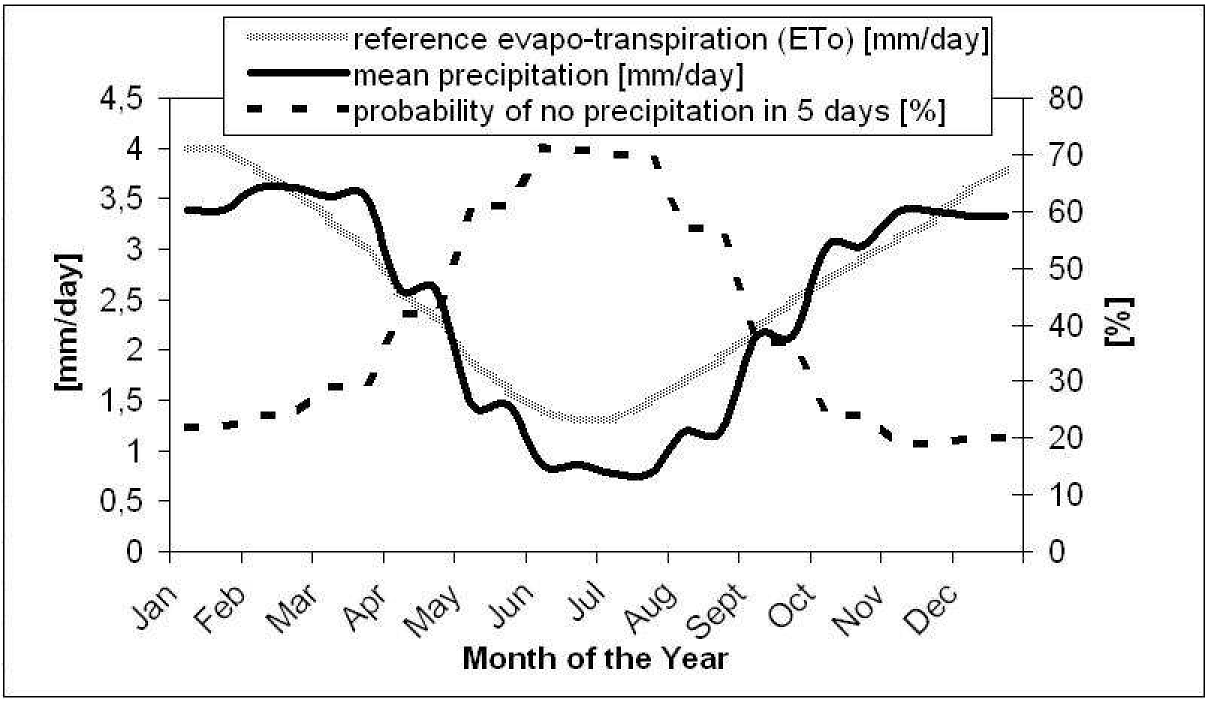

Figure 5-4: Visualized climatic data at Magabheni community gardens retrieved by [http: 9 and New_LocClim[5]].

5.2 Literature study

5.2.1 Wastewater characteristics

Chemical wastewater quality

Dependent on climatic conditions, cultural and individual water consumption habits, water supply- and wastewater collection systems; composition and quantity of municipal wastewater varies significantly in total but also seasonal and daily (Metcalf and Eddy, 2003; Pettygrove and Asano, 1985). Typical quantity of municipal wastewater (sewage) dependent of flow rates per capital is presented in Table 5-7.

[5] New_LocClim, Local climate estimator, Food and Agriculture Organisation (FAO) and German Weather Service (DWD), 2005; downloaded on 8.11.2009 from: www.fao.org/nr/climpag/pub/en3_051002_en.asp

Table 5-7: Typical composition of untreated domestic wastewater (source: Metcalf and Eddy, 2003:186)

Contaminants	Unit	Concentration (strength) [a]		
		Low	Medium	High
Solid, total (TS)	mg/L	390	720	1230
Dissolved, total (TDS)	mg/L	270	500	860
Fixed	mg/L	160	300	520
Volatile	mg/L	110	200	340
Suspended solids (SS)	mg/L	120	210	400
Fixed	mg/L	25	50	85
Volatile	mg/L	95	160	315
Settleable solids	mg/L	5	10	20
BOD_5, 20℃	mg/L	110	190	350
TOC	mg/L	80	140	260
COD	mg/L	250	430	800
Nitrogen, total	mg/L	20	40	70
Organic	mg/L	8	15	25
Free ammonia	mg/L	12	25	45
Nitrites	mg/L	0	0	0
Nitrates	mg/L	0	0	0
Phosphorus, total	mg/L	4	7	12
Organic	mg/L	1	2	4
Inorganic	mg/L	3	5	8
Chloride	mg/L	30	50	90
Sulphate	mg/L	20	30	50
Alkalinity (as $CaCO_3$)	mg/L	50	100	200
pH-Value [b]	-	6,5-8,5	6,5-8,5	6,5-8,5

[a] Low strength is based on an approximate wastewater flow rate of 750 L/capital · day
Medium strength is based on an approximate wastewater flow rate of 460 L/capital · day
High strength is based on an approximate wastewater flow rate of 240 L/capital · day
[b] (source: Pettygrove and Asano, 1985)

Metcalf and Eddy (2003) give some indications for the increase of mineral substances due to domestic water use as summarized in Table 5-8. The concentration of mineral substances is not altered significantly by wastewater treatment processes since they are no target substances for treatment (Metcalf and Eddy, 2003).

Table 5-8: Typical mineral increase for domestic water use based on 460 L / capital · day (source: Metcalf and Eddy, 2003:187)

Constituent	Increment range [mg/L]
Anions:	
Bicarbonates (HCO_3)	50 – 100
Carbonates (CO_3)	0 – 10
Chloride (Cl)	20 – 50
Sulphate (SO_4)	15 – 30
Cations:	
Calcium (Ca)	6 – 16
Magnesium (Mg)	4 – 10
Potassium (K)	7 – 15
Sodium (Na)	40 – 70
Other constituents:	
Aluminium (Al)	0,1 – 0,2
Boron (B)	0,1 – 0,2
Fluoride (F)	0,2 – 0,4
Manganese (Mn)	0,2 – 0,4
Silica (SiO_2)	2 - 10
Total alkalinity (as $CaCO_3$)	60 – 120
Total dissolved solids (TDS)	150 - 380

Microbial wastewater quality

Feachem et al. (1983) estimate selected pathogen concentrations in sewage of a fictive tropical community of 50 000 inhabitants in a developing country based on a large literature review. The community is expected to produce 100 litres of sewage per person per day and 90% of the pathogens do not enter the sewers or are inactivated in the first few minutes after excretion. Also Metcalf and Eddy (2003) present microbial concentrations in a typical wastewater. The information on approximation of pathogen concentrations in raw sewage are presented in Table 5-9. For the quantitative relation of indicator organism with potential pathogens a number of assumptions have to be taken which are included in the table.

Feachem et al. (1983) state that the total coliforms of warm blooded animals are composed generally to >90% of *E. coli*. The author decides to use the closest quantitative relation (90% of 10^7 - 10^9 total coliforms presented in Metcalf and Eddy (2003)) to rather overestimate pathogen concentrations, than underestimate them. Analytical data of the most popular indicator organism *E.coli* will be used as reference point. Another assumption used is that enteric viruses consist to 10 % of *rotaviruses* (Feachem et al., 1983).

Table 5-9: Microorganism populations in untreated domestic wastewater

Organism	Concentration [MPN/100mL][b]	Concentration [MPN/100mL][c]
	Bacteria	
Coliform		10^7 - 10^9 (total) 10^6 - 10^8 (faecal)
E.coli	$9 \cdot 10^6$ – 10^8	
Faecal streptococci		10^4 - 10^7
Shigella	700	10^0 - 10^3
Salmonella	700	10^2 - 10^4
Vibrio cholerae	1	
Pseudomonas aeroginosa		10^3 - 10^6
Clostridium perfringens		10^3 - 10^5
	Viruses	
Enteric virus	500	10^3 - 10^4
Rotavirus	10^2 – 10^3	
	Helminth	
Helminth ova		10^1 - 10^3
Ascaris lumbricoides	60	10^{-2} - 10^0
	Protozoa	
Protozoan cysts	10^3 [a]	
Campylobacter jejuni	10^{-1} – 10^3 [d]	

[a](source: Pettygrove and Asano, 1985:10-8)
[b](source: Feachem et al., 1983:17)
[c](source: Metcalf and Eddy, 2003:111)
[d](source: WHO, 2006: 25)

5.2.2 Risks attached to wastewater irrigation

Three domains of risks attached to agricultural irrigation with treated wastewater are presented in this chapter. Microbial and chemical contamination of treated wastewater has to be discussed separately in their characterisation of potential hazardous effects on health, environment and agronomic system.

In this document health risks are discussed mainly in respect to potential microbial health threats posed to consumers of agricultural products irrigated with treated wastewater.

For evaluation of microbial health risks posed to consumers of agricultural products a Quantitative Microbial Risk Assessment (QMRA) will be developed.

Risk for the agronomic system and environmental pollution risks will be discussed mainly on the basis of literature data and guidelines for irrigation water quality.

5.2.2.1 Health risk for consumers

Long term health risks for consumers of agricultural products irrigated with treated wastewater can arise from chemical wastewater constituents (Box 2). In this document, long term health risks will not be further discussed due to lack of analytical data and under the assumption of insignificance in comparison to microbial health risk in the context of the study area.

Box 2: Long term health risk for consumers of agricultural products

Long term health risk for consumers of agricultural products can originate from heavy metals, disinfection by-products, pharmaceuticals and endocrine disruptors. If these substances accumulate in the environment and enter the food chain they might pose risk to consumers health and the environment (Toze, 2006). Heavy metals in wastewater might accumulate in soil and become bioavailable for crops but origin mainly from industrial sources and will not discussed further in the context of municipal wastewater.

Disinfection by-products might be formed during chlorination in post treatment but tend to be present at very low concentrations in effluent and require the ingestion of large doses over long time periods to produce any clinical effect (Toze, 2006). Due to this rationale they will not be further discussed for health concerns.

Trace organics are found in domestic wastewater since a considerable fraction of active substances of ingested medical products are excreted unmodified. These substances originating from wastewater treatment plant effluent are known to be capable of affecting water organisms of receiving water bodies (Toze, 2006). Elimination of trace organics in wastewater treatment processes is very problematic. Trace organics are present in immense variety. Certain, costly, treatment mechanisms target only specific substances and the effect of treatment on not targeted trace organics in form of modification in other, potentially more critical forms is unknown but observed for some cases (Kümmer, 2009). Soil, with its high microbial activity and big adsorption and chemical redox capacity might be in comparison to water bodies the more effective degradation environment for these organic substances (Vinnerås, 2009). The potential treatment capacity of the soil for trace organics is also supported by studies on drinking water in Berlin, Germany which is successfully treated for a large amount of trace organics by the ground passage in soil aquifer treatment (river bank filtration process) (Gnirss et al., 2009).

The focus of this research is on health risk for consumers of wastewater irrigated crops. Health risk in this sense describes the risk to be infected and become ill with an infectious disease. A disease is infectious if it can be transmitted from one person to another or from an animal. During the transmission pathogens may be exposed to the environment, and their passage to the body of a new host organism can be impeded by changes in the environment (Metcalf and Eddy, 2003). Pathogens relevant for human health found in wastewater are enteric in origin. This means that theses pathogens are found almost exclusively in faeces and enter wastewater though sanitation (e.g. the toilet). Diseases are transmitted by ingestion of excreted pathogens. There are several ways of transmission as can seen in the so-called faecal-oral transmission routes which are depicted in Figure 5-5.

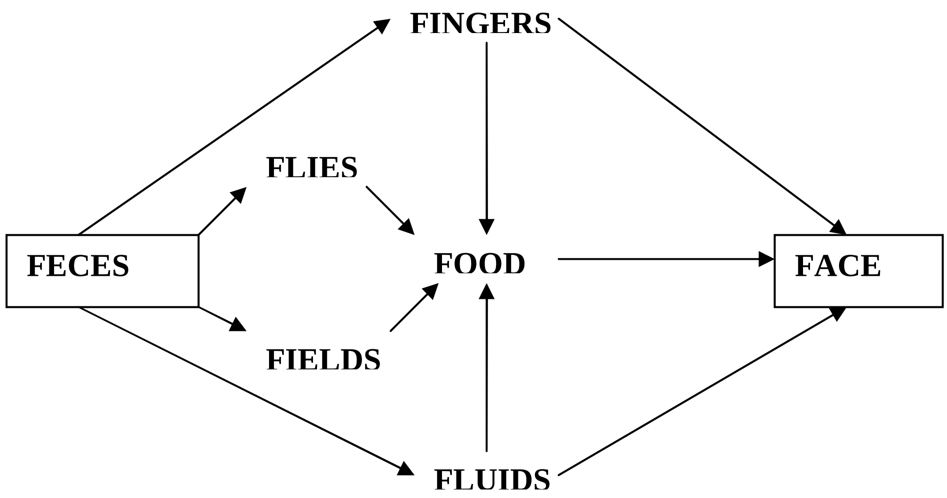

Figure 5-5: The F-diagram summarizes the main ways diarrhoea is spread: by faecal pathogens contaminating fingers, flies, fields, food and fluids and the swallowed (source: Esrey et al. 1998:9).

In this document the focus lies on exploration of the transmission route faeces – fields – food – face (wastewater irrigation of eatable crops) and other transmission routes are ignored despite the fact that they might be more relevant for human health.

All infectious diseases are caused by pathogens that are classified as bacteria, viruses, protozoa and helminth (UNEP, 2005). Gerba and Smith (2005) state that more than 150 known enteric pathogens may be present in untreated human wastes, and one new enteric pathogen has been discovered every year over the past decade. Some of the key pathogens found in municipal wastewater are summarized in Table 5-10. The risk of infection from any of these pathogens depends on a range of factors including pathogen numbers and dispersion in water, the infective dose required and the susceptibility of an exposed population, the degree of faecal contamination of the water and amount of treatment undertaken before potential exposure to crops and later crop consumers (Toze, 2006).

Table 5-10: Example of pathogens associated with municipal wastewater (UNEP, 2005)

Viruses	Hepatitis A virus, *Rotaviruses, Enteroviruses*
Bacteria	*Salmonella sp, Vibrio cholerae, Legionellaceae*
Helminth	*Ascaris, Toxocara, Taenia* (tapeworm), *Ancylostoma* (hookworm)
Protozoa	*Giardia lamblia, Cryptosporidium sp.*

Viruses

"Enteric viruses are the smallest of the pathogens found in water. They are all obligate intercellular parasites that require the infection of host cells of a suitable host and then force the host cell to produce multiple copies of the virus (Toze, 1997). This lack of ability to self-replicate means that viruses are present in water as inactive particles." (Toze, 2006: 149) According to Carducci et al. (2009) enteric Viruses most commonly found in human faeces are belonging to more than 140 types.

Bacteria

Bacteria are the most common of the microbial pathogens found in wastewater. A wide range of bacterial pathogens can be detected in wastewaters. Bacterial pathogens are metabolically active microorganisms that are capable of self-replication and are therefore, theoretically capable of replicating in the environment. However, the large majority of bacteria have high die-off rates when exposed to environmental conditions (Toze, 2006).

Helminth

Helminth (nematodes and tape worms) are common intestinal parasites transmitted via the faecal-oral route. "One of the major sources of helminth infections around the world is the use of raw or partially-treated sewage effluent and sludge for the irrigation of food crops (WHO, 1989)" (Toze, 2006:151) Helminth can produce eggs for replication which are very resistant to harsh environmental conditions and have long survival time in soil and water (WHO, 2006).

Protozoa

Protozoa are parasitic organisms which can produce cysts resistant to extreme environmental conditions. However, only little evidence concerning health risk by protozoa in wastewater irrigation is available (WHO, 2006).

Management of health risks

In developing economies and water scarce areas, the primary concern for irrigation with treated wastewater, is to balance the need for water and increased agricultural output, with attached public health risks. The WHO guidelines on wastewater use in agriculture from 2006 are particular relevant and attempt to approach the issue in an integrated way. "The risk management approach facilitates a flexible approach to defining a level of health protection and control measures that take into account local circumstances." (Godfree and Godfrey, 2008:353). The WHO (2006) guidelines on wastewater use in agriculture recognize the use of wastewater in agriculture as a mean to maximize public health and livelihood benefits while respecting the need to minimize the transmission of infectious agents. To balance benefits and risks the *Stockholm Framework* is introduced providing a harmonized framework for the development of health-based targets for water- and sanitation-related microbial hazards representing an acceptable additional disease burden by wastewater irrigation. The exposure to different concentrations of pathogens through consumption of wastewater irrigated products is associated with a certain level of risk. A health-based target uses a tolerable risk of additional disease as a baseline to set specific performance targets for wastewater management and food production that will reduce the risk of disease up to this level. To ensure effective health protection and improvement, targets can be adjusted (also over time) to be realistic and relevant to local conditions like financial, technical and institutional resources. Furthermore a health based target of 10^{-6} DALY (see Box 3) which can be adjusted by local authority for a specific context is suggested (WHO, 2006). In this research 10^{-6} DALY is used since the South African government does not provide contextual health based targets.

The effectiveness of all later discussed processes that modify DALY or amount of pathogens in wastewater will be quantified with log removal rates. A reduction of 90% is equal to 1 log reduction, a 99% reduction is a 2 log decrease and a 99,9% reduction is a 3 log decrease.

Box 3: WHO definition of DALY (source: [http: 13])

Disability – Adjusted Live Year (DALY): Quantifying the burden of disease from mortality and morbidity. One DALY can be thought of as one lost year of “healthy” life. The sum of these DALYs across the population, or the burden of disease, can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability. DALYs for a disease or health condition are calculated as the sum of years of life lost due to premature mortality and the years lost due to disability for incident cases of the health condition. Example: 10^{-6} DALY are equal to: one case of cancer per 100 000 persons exposed to health risk or one case of mild diarrhea per 1 000 persons exposed to a hazard (WHO, 2006).

WHO (2006) suggests to use a Quantitative Microbial Risk Assessment (QMRA) to assess the microbial health risk associated with consumption of agricultural products irrigated with wastewater. In the following, a QMRA for application in the case of Magabheni is elaborated.

5.2.2.2 Quantitative Microbial Risk Assessment

Soller et al. (2004) compare two ways of modelling microbial health risks. (1) Static models, originating from chemical risk assessment methodologies and (2) dynamic models, which include complex secondary infection roots that respect characteristics of microbial infections.

The most important differences are presented in Table 5-11. Due to restrictions in scope of this research only static modelling will be performed.

Table 5-11: Comparison of Static and Dynamic Risk Assessment Models (source: Soller et al., 2004:3-2)

Static risk assessment model	Dynamic risk assessment model
Static representation.	Dynamic representation.
Direct exposure (environment-to-person).	Direct (environment-to-person) and indirect exposure (person-to-person).
Individual-based risk.	Population-based risk.
Potential for secondary transmission of infection or disease is negligible.	Potential for secondary or person-to-person transmission of infection or disease exists.
Immunity to infection from microbial agents is negligible.	Exposed individuals may not be susceptible to infection or disease because they may already be infected or may be immune from infection due to prior exposure.
Dose-response function is the critical health component.	The dose-response function is important; however, factors specific to the transmission of infectious diseases may also be important.

This chapter describes how the health risk for consumers will be assessed with QMRA on basis of the WHO 2006 Guidelines, Volume 2: Wastewater Use in Agriculture.

The National Academy of Sciences of the USA published in 1983 the "Red Book" on chemical risk assessment defining risk assessment to be composed of four steps presented in the left column of Table 5-12. Static microbial risk assessment is based on the same four step process, though each step is adapted to microbial health risks (Haas et al., 1999).

Table 5-12: Four steps of Microbial Risk Assessment (modified from Haas et al., 1999)

Hazard identification	Identification of microbial agents their rout of transmission and the spectrum of human illnesses and diseases associated based on endemic and epidemic diseases investigation, case studies, hospitalization studies etc.
Exposure assessment	Determine the size and nature of the population exposed and the route, concentrations, and distribution of the microorganisms and the duration for the exposure.
Dose-response assessment/ model	Mathematically characterize the relationship between the dose of pathogens administered and the probability of infection or disease in the exposed population.
Risk characterization	Estimating the magnitude of the public health problem, understanding the variability, and uncertainty of the hazard.[a]

[a]This definition encompasses essentially four distributions which have to be evaluated according to assumptions made and uncertainty of the previous steps.
1. The spectrum of health outcomes
2. The confidence limits surrounding the dose-response model
3. The distribution of the occurrence of the microorganism
4. The exposure distribution

The presented sequential four step process for microbial risk assessment has to be customized for each case. In the following the development of the adopted QMRA is elaborated. The developed QMRA scheme can be found in Appendix 9. The exposure assessment is based on the production chain for wastewater irrigated crops till the farm gate. Later contamination during harvest storage, transport, marketing etc. is not assessed.

The hazard identification is the first step and serves the purpose of identifying which hazards exactly exist in the system. In the case of wastewater irrigation the most relevant hazards origin from excreted pathogens of infected hosts in the wastewater generating community. Pathogens can be determined by epidemiologic studies on the community and/or regional epidemiologic literature. Skin and internal infections should be distinguished since different pathogens are responsible but both can be found in household wastewater. Since it is not possible to model the whole QMRA on all pathogens the most relevant for the intended irrigation are chosen which exclude those responsible for skin infections. They should be water born, persistent in the environment with a low infectious dose for the host and with serous symptoms. In the best case they should be detectable in an available laboratory. For the model it is crucial that previous research developed a dose response model to quantify toxicity of the pathogen. As later presented in the case study this is only the case for a limited amount of pathogens. Since microbial and viral analysis are expensive and require well equipped laboratories, certain indicator organisms have to be chosen. These do not have to be pathogenic themselves, but need to relate in number to the pathogens of interest which are usually representatives of bacteria, viruses and parasites.

The second step; exposure assessment includes all stages of the production chain and intends to quantify the effect of each stage on the final health risk consumers are exposed to. Health risk for consumers is dependent of the pathogen concentration in wastewater used for irrigation, the amount of wastewater that gets in contact with the crop, how much pathogens die off on the crop and how the crop is handled and prepared for consumption. Due to a lack of quantifying data in the literature the exposure assessment can only be performed by taking a number of assumptions. Taking assumptions for QMRA due to insufficient database is also recommended by WHO (2006). The assumingly most relevant aspects from the outlet of the treatment facility onwards are picked up and discussed later in this chapter. The selected steps are: Irrigation water storage, irrigation method, volume of applied wastewater, crop choice and environmental decay.

The dose response modelling step is done with the QMRA Monte Carlo simulation program (Andrew Hamilton method) provided by Leeds University. The Microsoft Excel based programme calculates the annual risk of infection with input of target pathogen, dose and frequency of exposure and expected pathogens on the crop.

Annual risk of infection can be calculated by data provided on particular organisms by WHO (2006) into DALY values. Calculated DALY can be evaluated against the tolerable burden of disease of 10^{-6} DALY provided by WHO (2006) guidelines for wastewater use in agriculture.

In the following the QMRA step: exposure assessment is discussed and taken assumptions are justified.

Irrigation water storage

Evidence from scientific literature suggests that irrigation water storage can enhance bacteria re-growth but also reduce pathogen concentration in wastewater and could in this serve as post treatment step.

Irrigation water storages have to be distinguished in small on-farm operational water storage for managing daily flow fluctuations and larger seasonal storage and treatment reservoirs (Keraita et al., 2008). In terms of pathogen reduction, Finley (2008) presents contradictory publications on small grey water storages. While Dixon et al. (2000) find a potential reduction of pathogens after 24h and 48h storage; Rose et al. (1991) find a 1 to 2 log increase in total and faecal coliform count after two days storage (Finley, 2008). Consequently no clear conclusion can be made at this point.

Seasonal water storage reservoirs are much bigger than operational storages and enable farmers to store excess water in the wet season to use it in the dry season. Hamilton et al. (2005) distinguish different pathogen groups: Viruses, Bacteria and Fungi which could be reduced or grow during irrigation water storage. Viruses can not grow in seasonal irrigation water storage since hosts are lacking, though Bacteria and Fungi can grow dependent on the environmental conditions, but in general detailed re-growth models are lacking (Hamilton et al., 2005). Nevertheless "several researches (Dor and Raber, 1990; Indelicato et al., 1996, 1997; Juanico and Dor, 1999, Barbagallo et al., 2003) have established that, under proper conditions, water storage can lead to significant improvement in irrigation water quality" (Mancini et al., 2007:417-418). In the WHO Guidelines (2006) storage and treatment reservoirs with a depth of 5-15 meters are described to have the same treatment efficiency as a waste stabilization pond but with decreased evaporation losses – "i.e. a 2-4 Log-unit removal of viruses, a 3-6 Log-unit removal of bacterial pathogens, a 1-2 Log-unit removal of protozoan (oo) cysts and a 3 Log-unit removal of helminth eggs." (WHO, 2006:86).

Irrigation method

Conventional irrigation methods can be divided into surface irrigation (basin, furrow or border irrigation), sprinkler irrigation, micro-irrigation (drip, trickle, and bubbler) and sub surface irrigation (Gerbrandy and Levelt, 2005). For wastewater irrigation also watering cans is used frequently as a labour intense method.

The choice of an irrigation system for wastewater irrigation has four dimensions:

- field application efficiency
- contact of irrigation water with crop surface
- microbial health risks for farmers and local community
- local applicability of irrigation technology.

Field application efficiency describes the relation of the amount of water supplied to the field and the amount of water that reaches the crop in order to cover crop water requirement. For the evaluation of health risks, poor field application efficiency results in supply of high amounts of irrigation water which transports high amounts of pathogens to the field.

In Finley (2008), Gerba and Smith (2005) argue that contact of irrigation water with crop surface of above-ground crops is the most important factor in evaluation of health risk for crop consumers. Experimental studies of Enriquez et al. (2003), Sadovski et al. (1978), Armon et al. (1994) and Oron (2002) support the relation of irrigation method with pathogen contamination of plant surface. Armon et al. (1994) found that transmission of protozoan cysts from effluent onto zucchini surfaces is significantly higher by sprinkler irrigation then by subsurface or surface application. Sadovski et al. (1978) show that drip irrigation with contaminated irrigation water reduces crop contamination to a minimum in comparison to sprinkler irrigation. Enriquez et al. (2003) find that subsurface drip irrigation yields in even lower crop contamination than drip irrigation. Tilley et al. (2008) recommends that only drip and surface irrigation methods are feasible for wastewater application and spray/sprinkler irrigation should be avoided due to increased evaporation and uncontrolled plant contamination with pathogens. Evidence from these studies allows the classification of irrigation methods in degrees of plant surface contamination of above ground crops (Table 5-13). It is important to recognize that epidemiologic evaluation of irrigation methods can only be done case specific for the type of irrigated crop. “Although ‘low contaminating’ irrigation practices (i.e. drip irrigation) have been suggested to reduce residual contamination, it may become critical to ‘root’ crops (e.g. carrots, onion) when low-quality effluents are applied.” (Armon et al. 1994:247) However, this statement is also contested by experiments with land application of effluent that show that most of applied coliforms were retained in the top 7,5 cm of soil (Crites et al., 2000). The mechanisms of plant surface contamination are further discussed in the following subchapter: Crop choice.

In comparison to all other irrigation methods, sprinklers have an additional dimension in terms of health risk. Sprinklers spray water though a pressurized system in fine droplets in the air. A cloud of fine disperse water opposed to wind drift can affect farmers and near by communities. Not only the whole body surface can be contaminated but aerosols might carry pathogens into the respiratory system of exposed people (Mara and Caimcross, 1989 in Fegan et al., 1998). Additionally intense odour nuisance might occur.

Water quality is an important factor when choosing an irrigation method for a certain case. Localized irrigation usually works with low discharge emitters that release almost continuously water from a low pressure system though fine nozzles. Besides of high costs, required knowledge and a pressurized supply system these emitters are sensitive to biological, chemical and physical clogging (Boesveld, 2008). In wastewater irrigation, localized irrigation methods require filtration of effluent in order to remove suspended solids and control of chemical and biological water parameters during system operation (Fegan, et al. 1998).

In Table 5-13 one can see the summarized features of each irrigation method.

Table 5-13: Factors affecting choice of irrigation method, and special measures required when wastewater is used (adapted from Fegan et al. 1998)

Irrigation method	Description	Factors affecting choice	Special measures for wastewater
Flood Irrigation	Wetting almost all the land surface	Lowest cost, exact levelling not required, low field application efficiency	High protection for field workers, crop handlers and consumers
Furrow irrigation	Wetting only part of the ground surface	Low cost, levelling may be needed, medium filed application efficiency	Protection for field workers, possibly for crop handlers and consumers
Sprinkler (spray) irrigation	Wetting of the soil occurs in much the same way as by rain Requires pressurized supply system	Medium costs and medium field application efficiency	Minimum distance 50-100 m form houses and roads, anaerobic wastes should not be used because of odour. Protection of field workers.
Subsurface and Localized irrigation	The subsoil is saturated by subsurface irrigation, water is applied to each individual plant in localized (trickle,, drip or bubbler) irrigation	High costs and high field application efficiency	Filtration and potential pH adjustment (<7) is needed to prevent clogging of emitters
Watering Can	Very labour intensive, yet efficient	Low costs, labour availability	Adjusted application, modified emitter head (sieve, removal of spray head)

<u>Volume of applied irrigation water</u>

Volume of applied irrigation water is an important factor for evaluation of health risks for consumers since it determines the amount of pathogens reaching the field. The volume of wastewater that needs to be applied is dependent on planted crops, cropping calendar, climatic conditions including precipitation and field application efficiency.

Plants have certain water requirements since their growth is depended on transpiration and photosynthesis. Irrigation is needed if rainfall is not enough. Volume and frequency of applied irrigation is dependent of the physical conditions of plant-water-atmosphere and properties of the soil profile which acts as soil moisture reservoir. Furthermore required water supply is dependent of skills, knowledge, irrigation and land management and other characteristics of farmers practice (Dries and Gerbrandy, 2005). Required irrigation water supply can be estimated under consideration of the plant-water-atmosphere relationship.

To know the evapo-transpiration of a certain crop at a specific location and time the so called reference evapo-transpiration can be calculated. Reference evapo-transpiration can be calculated with help of the FAO Penman-Monteith equation. There are many microclimatic data required which are often not available. The modulation program *New_LocClim*[6] can be used to estimate local climatic conditions including the potential evapo-transpiration as explained above. The crop coefficient (Kc) permits to link the reference evapo-transpiration ET_0 of a location with a specific crop and to calculate the evapo-transpiration following Equation 3.

Equation 3

$ETc = Kc * ET_0$.

The Kc values and growing stages are based on FAO data (FAO, 1998). In the FAO paper are also planting times given, but the cropping calendar of local farmers can be used as well. With the planting dates, evapo-transpiration and statistical local rainfall data the irrigation requirements can be calculated.

<u>Crop choice</u>

Crops irrigated with treated wastewater can be categorized in terms of health risks for consumers since health risk originate mainly from pathogens attached to the plant body and can be reduced significantly by preparation practice before consumption as elaborated later. A matrix of distinguished crop groups due to required preparation for consumption and location of growth with crop examples can be seen in Table 5-14.

Table 5-14: Developed matrix of distinguished crops in terms of potential health risks for consumers.

	Consumed raw	Consumed peeled	Consumed cooked
Grown subsurface (root vegetables)	Carrot	Onion	Potato
Grown above ground (low)	Cabbage	?	Pumpkin
Grown above ground (high)	Tomato	Banana	Corn

According to WHO (2006) cooking can reduce pathogens on crops with 5-6 Log-units and peeling of crops with 2 Log-units. The location of growth in combination with the irrigation method is determining the amount of pathogens reaching the crop. For subsurface irrigation corn would represent the crop with least health risks attached and carrots might represent the crop with highest health risks attached. Apart from the location of growth also plant

[6] New_LocClim, Local climate estimator, Food and Agriculture Organisation (FAO) and German Weather Service (DWD), 2005; downloaded on 8.11.2009 from: www.fao.org/nr/climpag/pub/en3_051002_en.asp

physiology and surface structure might influence irrigation water potentially remaining on the crop. Smooth leave surface will let irrigation water on leaves roll off, whereas coarse structure will retain more water.

For the case study, a number of assumptions have to be taken to estimate contamination of crops by irrigation water.

Potential contamination of root vegetables with treated wastewater is extremely difficult to predict due to poor literature data. Oron (2002) shows that soil moisture is enabling movement and survival of pathogens in soil. “The main factors affecting survival of the microorganisms are the soil characteristics and actual moisture.”(Oron, 2002: *html*) Experimental results also show that the build-up of pathogenic microorganisms in receiving soils is complex due to species specific survival rates and patterns of movement in the subsurface (Oron, 2002). Accumulation of pathogens in soil is found by Casanova et al. (2001) who describe significantly higher levels of faecal coliforms and *E.Coli* in greywater irrigated soil plots in comparison to freshwater irrigated plots.

The splash of contaminated soil on plant surface due to rain or irrigation activity is a contamination route for above soil plants. Pathogens can occur on plants by its growth though contaminated soil and though dust or the activities of workers, birds and insects (Bryan, 1977 in Fegan et al. 1998). Pathogen contamination of the plant inner by water sucked up with the root system is not likely to occur. Already in 1925, Mills et al. found that uninjured fruits and vegetables do not contain bacteria within their tissue since particle matter and pathogens can not pass the osmotic barrier of plant roots. This was confirmed for viruses by Crites et al. (2000).

<u>Environmental decay</u>

Pathogenic organisms in low quality irrigation water on crop and soil are exposed to the environment. Experimental and epidemiological studies from Mills et al. (1925), Mara et al. (2007), Gerba and Smith (2005), Shuval et al. (1997) and Fegan et al. (1998) prove that exposed pathogenic organisms have specific mortality ratios in a function of time, location and environmental conditions.

Environmental factors like high temperatures, sunlight and low air humidity promote death of pathogens by UV radiation and desiccation (Fegan et al., 1998). Pathogen decay rates depend strongly on the environmental conditions of the specific location. Decay rates in different soil types, on root crops, above ground crops and even different phenotypes of above ground crops differ significantly.

Different authors agree that the survival of pathogens in the soil varies greatly over the different types of soil and pathogens. Factors influencing survival of enteric bacteria in the soil are indicated in Table 5-15.

Table 5-15: Factors affecting survival of enteric bacteria in soil (source: Gerba et al. (1975) in Fegan et al. (1998))

Factor	Remarks
Moisture content	Greater survival time in the moist soils and during times of high rainfall
Moisture holding	Survival time is less in sandy soils than in soils with greater water- holding capacity
Temperature	Longer survival at low temperatures, longer survival in winter than in summer
pH	Shorter survival time in acid soils (pH 3-5) than in alkaline soils
Sunlight	Shorter survival time at soil surface
Organic matter	Increased survival and possible re-growth when sufficient amounts of organic matter are present
Antagonism from soil micro flora	Increased survival time in sterile soil

Thus pathogen survival on crops is in general much shorter than survival in soil or water as the pathogens are not protected on the surface of the crops. The survival times vary greatly between different types of pathogens, particular species, crop types and different reviewed studies.

Course plant surface for instance or tightly coupled leaves can protect plant surface from exposure to sun light and consequently reduce pathogen die off (Hamilton et al., 2006).

Various pathogens have different survival times in the same environmental conditions. Table 5-16 shows approximate survival times on crop surface and in the soil for exemplary pathogens origin from contaminated irrigation water.

Table 5-16: Survival time (in days) of excreted pathogens on crops at 20-30 ℃ (from Fegan et al. (1998) adapted from Feacher et al (1983))

Pathogens		Survival time on crops [days]	Survival time in soil [days]
Viruses	Enteroviruses	< 60 but usually < 15	< 100 but usually < 20
Bacteria	Faecal coliforms	< 30 but usually < 15	< 70 but usually < 20
	Salmonella spp.	< 30 but usually < 15	< 70 but usually < 20
	Shigella spp.	< 10 but usually < 5	
	Vibrio cholerae	< 5 but usually < 2	<20 but usually <10
Protozoa	*Entamocha histoclytica cysts*	< 10 but usually < 2	<20 but usually <10
Helminths	*Ascaris lumbricoides eggs*	< 60 but usually < 30	Many month

As one can see in Table 5-16, Viruses have the longest survival rates after Helminth eggs since these are most resistant against desiccation. Due to the greater amount of viruses in wastewater, these will be used to model the decay function as a conservative indicator.

Hamilton et al. (2005) state that “the decay of pathogens in the environment can be modelled using a simple first-order rate equation such as:

Equation 4

$$f = \frac{\mu_{1_1}}{\mu_0} = e^{(-kt)}$$

Where f is the proportion of pathogens remaining (viable) after time t(d), μ_0 and μ_1 are the respective initial and final pathogen concentrations, and the slope parameter k is the decay coefficient (d^{-1})" (Hamilton et al., 2005:75). This simple linear model assumes that the decay coefficient stays constant over time and could be extended with a bi-phasic inactivation model (Hamilton et al., 2005). Due to a lack of detailed pathogen data this will be ignored in this case. The decay coefficient (k) 0,69/day introduced by Asano and Sakaji (1990) and Asano et al. (1992) will be used for the modelling of environmental decay (Hamilton, 2005 and Seidu et al., 2008).

Ayres et al. (1992) shows that the number of helminth eggs from continuous spray irrigation of wastewater do not increase as they are washed of by irrigation (Fegan et al., 1998). However this might not count for viruses and bacteria which are much smaller in size and might attach to plant surface. In later calculations wash off effects from plant surface are not considered due to insufficient data.

Sadovski et al. (1978) found that pathogen concentration in soil was decreasing at ongoing irrigation with fresh water much faster in light textured, well drained soils than in soils with a high bulk density. This indicates that there is a certain wash out expectable in soils and most likely also on plants.

5.2.2.3 Risks for the agronomic system

To evaluate risks for the agronomic system resulting from chemical water quality of irrigation water, literature on water quality recommendations for conventional irrigation and literature specifically about irrigation with treated wastewater was reviewed.

The FAO guidelines *Water quality for agriculture* (Ayers and Westcot, 1989) provides Table 5-17 to evaluate the feasibility of a given irrigation water for agricultural use. The presented guidelines are developed on basis of the long-term influence of water quality on crop production, soil conditions and farm management. The approximate separation in degree of restriction has to be adjusted to specific site conditions (e.g. soil and climate) and indicates the level of required response of agricultural management to a specific water quality. Full production capability of all crops in terms of water quality is assumed when the guidelines indicate no restrictions on use (Ayers and Westcot, 1989).

"For irrigation with reclaimed wastewater, therefore, the suitability of water is judged against the level of management needed to cope successfully with the water related problems that are expected to develop during use." (Pettygrove and Asano, 1985:3-10)

Table 5-17: Guidelines for interpretations of water quality for irrigation (Source: Ayers and Westcot, 1989: Chapter 1.4, Table1)

Potential Irrigation Problem		Units	Degree of Restriction on Use		
			None	Slight to Moderate	Severe
Salinity *(affects crop water availability)*[2]					
	EC_w	dS/m	< 0.7	0.7 – 3.0	> 3.0
	(or)				
	TDS	mg/l	< 450	450 – 2000	> 2000
Infiltration *(affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)*[3]					
SAR	= 0 – 3 and EC_w =		> 0.7	0.7 – 0.2	< 0.2
	= 3 – 6 =		> 1.2	1.2 – 0.3	< 0.3
	= 6 – 12 =		> 1.9	1.9 – 0.5	< 0.5
	= 12 – 20 =		> 2.9	2.9 – 1.3	< 1.3
	= 20 – 40 =		> 5.0	5.0 – 2.9	< 2.9
Specific Ion Toxicity *(affects sensitive crops)*					
	Sodium (Na)[4]				
	surface irrigation	SAR	< 3	3 – 9	> 9
	sprinkler irrigation	me/l	< 3	> 3	
	Chloride (Cl)[4]				
	surface irrigation	me/l	< 4	4 – 10	> 10
	sprinkler irrigation	me/l	< 3	> 3	
	Boron (B)[5]	mg/l	< 0.7	0.7 – 3.0	> 3.0
	Trace Elements (see Table 21)				
Miscellaneous Effects *(affects susceptible crops)*					
	Nitrogen (NO_3 - N)[6]	mg/l	< 5	5 – 30	> 30
	Bicarbonate (HCO_3)				
	(overhead sprinkling only)	me/l	< 1.5	1.5 – 8.5	> 8.5
	pH		**Normal Range 6.5 – 8.4**		

Pettygrove and Asano (1985) add some ions relevant in wastewater irrigation (Table 5-18) to the presented table. They suggest to use Table 5-17 with the modification to use instead of nitrogen (NO_3-N); total-N with the argumentation that all forms of nitrogen can be transformed into the other ones by microbial activity in the soil.

Table 5-18: Common irrigation water quality (source modified: Pettygrove and Asano, 1985)

Ion	Unit	Usual range in irrigation water
Calcium (Ca^{2+})	mg/L	0 – 400
Magnesium (Mg^{2+})	mg/L	0 – 60
Sulphate (SO_4^{2-})	mg/L	0 – 1000

South African legislation (DWAF, 1996b) provides wastewater unspecific water quality guidelines for irrigation presented in extract in Appendix 9.2 inclusive explanations.

Salinity

Literature suggests that salinity, measured by electrical conductivity, is the single most important parameter in determining the suitability of water for irrigation. It relates directly to possible problems and yield loss caused by the total salt load in irrigation water. Plant damage from both salinity and specific ions is usually tied closely to an increase in salinity.

Yield reductions occur when salts accumulate in the root zone to an extent that the osmotic potential of the soil water is too high for crops to extract sufficient water for development (Azers, 1985; Crites et al., 2000).

Another risk of irrigation with water with high sodium and low calcium content counts particularly for soil with high clay fraction. Clay particles have a net negative surface charge. The charge stands in equilibrium with cations present in soil water and a so called diffuse electrical double layers of cations-clay-cations is formed. These clay double layers expand if divalent cations like Calcium (Ca^{2+}) are exchanged with two monovalent ions like sodium (Na^{+}) which together have a larger size then one Calcium ion (ESW 30806 Reader, 2007). Swelling and dispersion can lead to ground clogging which might reduce the infiltration capacity of irrigation water dramatically (Toze, 2006). The proportion of sodium to calcium and magnesium in irrigation water is expressed with the Sodium Absorption Ratio (SAR).

Leaching is the key to controlling a water quality-related salinity problem. Over a period of time, salt removal by leaching must equal or exceed the salt additions from the applied water to prevent salt building up to a damaging concentration (Azers, 1985). A leaching fraction of 0,15 is usually applied for irrigation water with EC_W < 0,7 dS/m (Ayers and Westcot, 1989).

Nutrients

Nutrient concentrations in wastewater need to be analyzed to include the nutrient content in a potential fertilizer program. Experiences from California show that nutrients in wastewater occurring in quantities important for agriculture are nitrogen, phosphorus and occasionally potassium, zinc, boron, and sulphur. Despite the beneficial effect of nutrients for crop growth, over supply of nutrients can have a potential adverse effect on yield.

Nitrogen is considered to be most beneficial for crop growth but excessive supply particular in the phase of plant maturity can lead to dramatic yield reduction due to deformation and increased vulnerability to pests and parasites (Russell, 1973, Pettygrove and Asano, 1985). Boron is an essential plant micronutrient but has a risk of becoming quickly toxic if occurring in irrigation water in slightly higher concentrations (crop specific but usually <1 mg/L) than required (Pettygrove and Asano, 1985). For this reason a brief characterisation of nutrients in agronomic systems will be presented in this chapter.

"There are three possible sources from which roots can extract their nutrients: the soil solution, the exchangeable ions, and the readily decomposable minerals." (Russell, 1973:542) These three forms of nutrients stand in equilibrium to each other, and if any nutrients (except nitrate) are removed by crops from the soil solution at least a part of this loss will be made good from the non-soluble nutrient reserves in the soil. The solid material of the soil, keeps the soil solution well buffered both for pH and for all nutrients expect nitrates (Russell, 1973). In this sense and under consideration of soil microbial activity, any nutrient supplied by wastewater irrigation, either in solution or fixed in organic matter will become eventually bioavailable. Microbial transformation processes of nitrogen in soil will be discussed later in detail.

Supplying nutrients by effluent irrigation is assumed to be beneficial since even in conventional agriculture fertilizer applied through irrigation water is found to be a preferable fertilizer application method. Röber and Schaller (1985) argue that nutrient requirements and irrigation requirements are closely linked. If the plant is in a growing stage it has high water and nutrient requirements. It is favourable to apply nitrogen in small proportions over the whole growing period to increase plant uptake and avoid leaching. But also phosphorus is easier bioavailable if applied already dissolved in water (Rober and Schaller, 1985). Plants take up phosphorus almost exclusively as inorganic phosphate ions. Other forms of phosphate are most likely being hydrolyzed to ortho-phosphate before plants use them (Russel, 1973). The oversupply of phosphorus has no known negative effects in agriculture but is also not likely to happen with application of treated wastewater (Pettygrove and Asano, 1985).

Different species of plants have differing nutrient requirements and powers of extracting ions (Russell, 1973). The nutrient uptake rate is dependent on crop, growing stage, and site specific conditions and chemical appearance of the nutrients in fertilizer. Pettygrove and Asano (1985) present nitrogen utilization efficiencies of different crops in California for mineral fertilizer of 40 – 65%. This approximation is confirmed by Russell (1973) “Crops that respond to nitrogen manuring commonly take up a fix in their mature tissue between one-third and one-half of the nitrogen added as fertilizer; the remainder is lost to the crop and usually to the soil, probably being either denitrified or washed out into the subsoil during wet weather.” (Russell, 1973:37)

General mineral fertilizer recommendations for horticultural vegetables in Germany and average quantity of fertilizer applied in California are presented in Table 5-19. Pettygrove and Asano (1985) comment that supplied fertilizer in California are below crop requirements.

Table 5-19: Fertilizer recommendations for Germany and average applied fertilizer in California in kg nutrient per ha per year for vegetables.

Nutrient	Maintenance fertilization[a]	Fertilization for Increased yield[a]	Average fertilization in California[b]
Phosphorus (P_2O_5) [kg/ha·year]	100	150	96
Potassium (K_2O) [kg/ha·year]	300	400	67
Nitrogen (N) [kg/ha·year]	300[c]	400[c]	187

[a] source: Niesel-Lessenthin, 1988
[b] source: Pettygrove and Asano, 1985
[c] there are no general fertilizer recommendations available for nitrogen but an estimation based on nitrogen requirements of cabbage allows an approximation

The relation of amount of fertilizer application and yield response is presented in Figure 5-6. With higher nutrient levels each additional unit of fertilizer has a lower yield increase as response. Maintenance fertilization keeps the yield on an economic optimal, yield suboptimum. For nitrogen and boron the graph of the presented figure will drop with increasing fertilizer application, after reaching a certain optimum yield.

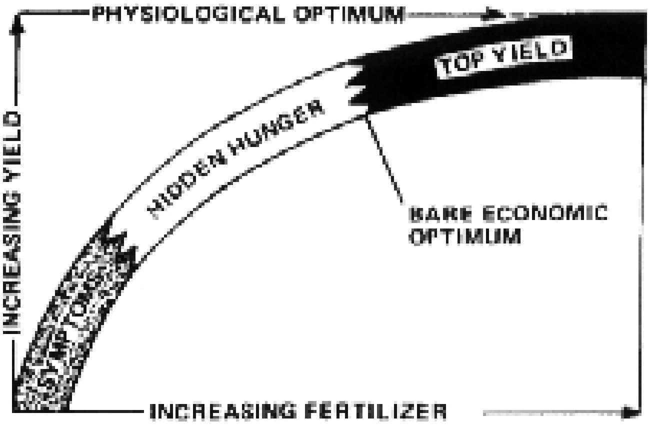

Figure 5-6: Schematic fertilizer- yield relationship (Herrera, 1998).

Case studies about micro nutrients reveal that zinc, sulphur and boron applied by irrigation with treated wastewater could be sufficient to correct nutrient deficits in agriculture without exceeding critical concentrations (Pettygrove and Asano, 1985).

<u>Trace metals</u>

An evaluation of 12 municipal treatment plant effluents in California (with unknown treatment technology) against maximal recommended concentrations of trace metals in irrigation water for California showed that in all but one cases the effluents were suitable for use in agriculture (Pettygrove and Asano, 1985:3-28). This information leaves the conclusion that trace metals in wastewater are no issue for the agronomic system and will not be further discussed; also since Magnesium is the only trace metals sampled and analysed in Magabheni pond effluent.

<u>Organic matter</u>

Dependent of the degree of pre-treatment high loads of organic matter might be transported to the agricultural field by irrigation with treated wastewater.

Organic matter origin from animal or human manure or plant residuals is thought to enhance soil quality of the agronomic system (Table 5-20) rather than to pose a risk to it. (ESW 30806, 2007).

Table 5-20: Effects of organic matter on soil fertility (source: Young 1989 in ESW 30806, 2007:190).

Primary effects	Consequences
Physical effects	
Binding of particles, root action leading to improved structural stability, balance between fine, medium and large pores	Improved root penetration, erosion resistance and moisture properties; water-holding capacity, permeability, aeration
Chemical effects	
Nutrient source, balanced supply, not subject to leaching, with slow, partly controllable, release	Including better response to fertilizers, non-acidifying source of N, mineralization of P in available forms
Complexion and enhanced availability of micronutrients	
Increased cation exchange	Better retention of fertilizer nutrients
Improved availability of P though blocking of fixation sites	
Biological effects	
Provision of a favourable environment of N fixation	
Enhanced faunal activity	

5.2.2.4 Risk for environmental pollution

For evaluation of environmental pollution risk from irrigation with treated wastewater in agriculture the treatment capacity of soil has to be considered. Applied irrigation water is infiltrating through the soil horizon and wastewater constituents are exposed to various filtration and removal mechanisms of soil, soil microorganisms and crops. Relevant environmental pollution risk origins mainly from leaching of non-biodegradable substances into the groundwater. The process is dependent on the amount of applied contaminants and removal efficiency of the soil.

For evaluation of treatment capacity of the soil, irrigation with treated wastewater can be regard as a form of land treatment. “Land treatment is defined as the controlled application of wastes onto the land surface to achieve a specified level of treatment though natural physical, chemical, and biological processes within the plant-soil-water matrix.” (Crites et al. 2000:7) Crops enhance treatment capacity of soil due to removal of nutrients by crop uptake, reduced erosion, aeration of the soil and maintenance or increase of infiltration rates (Crites et al. 2000). In the following, removal mechanisms and efficiencies of relevant wastewater constituents will be discussed.

Box 4: Definition of land treatment for wastewater (Crites et al. 2000).

> The concept of land treatment for wastewater includes slow rate, rapid infiltration and overland flow. In this text the reference to land treatment always describes slow rate application, which is typically either on cultivated or uncultivated ground, with moderate soil permeability, ground water depth of 0,6-3,0m and annual hydraulic loading of 0,6-6,0 m in weekly application of 0,5-4 times.

Organic substances

Land application is an efficient method to remove biodegradable organic component, typically characterized as biochemical oxygen demand (BOD_5) from infiltrating water. Removal mechanisms include filtration, adsorption, and biological reduction and oxidation (Crites et al., 2000). Experiences from long term land application of wastewater in the US show that high hydraulic - and organic loading can be applied while sustaining high removal rates. Crites et al. (2000) present an example of land application of municipal sewage with hydraulic loading rates of 7,6 m/year and a BOD_5 of 92 mg/L where after percolating though soil the measured BOD_5 concentration is between 0,9-1,7 mg/L. The presented removal efficiency of 98% after 1,5 m infiltration and other examples of removal rates suggest the conclusion “that land treatment with municipal wastewater, at 200-300 mg/L $BOD_{5,}$ should be no problem.” (Crites et al., 2000:20)

Total Suspended Solids

Crites et al. (2000) present an example for land treatment with a loading of 120 mg/L total suspended solids (TSS) achieving a effluent quality measured at 1,5 m depth of <1 mg/L (TSS). Suspended solids are removed by filtration in the soil profile and since municipal effluents are mainly composed of biodegradable organics the residual in the soil profile will be decomposed. As a result, the amount of suspended solids in typical municipal wastewater (30-350 mg/L TSS) should not be the limiting factor for land treatment (Crites et al., 2000).

Pathogenic organisms

Land treatment systems target also pathogens, grouped in parasites, bacteria and viruses. Effective removal mechanisms during land application are: adsorption, desiccation, radiation, filtration, predation, and exposure to other adverse conditions achieving a five log (10^5) reduction of faecal coliforms within less than 1 m infiltration (Crites et al., 2000).

Percolation risk of pathogens is strongly dependent of the soil texture. In general, finer-textured soils found in agriculture achieve highest removal rates. 10^5 CFU/100 mL faecal coliforms in primary effluent of a municipal wastewater treatment plant are found to be removed completely by filtration though 1,5 m soil profile of fine-textured silt loam as well as in coarse-textured loamy sand (Crites et al., 2000).

Virus removal is dependent on adsorption reactions, which is also highly efficient in fine-textured agricultural soils. Research of Lance et al. (1980) on high rate infiltration systems (10-20 times higher hydraulic loading rates than in conventional land treatment applications) presented in Crites et al. (2000) indicated a relation of infiltration rate and virus movement (adsorption-resorption equilibrium) in soil. In column experiments with calcareous sand only extreme hydraulic loadings from 0,6 to 1,2 m/d caused viral breakthrough (Crites et al., 2000).

Pettygrove and Asano (1985) confirm that soil is an effective filter of pathogens (including viruses) to avoid groundwater contamination from irrigation with treated wastewater.

In land application relatively large eggs of parasites like Helminth will be filtered and remain in the soil profile where, under optimum conditions, they can survive for years. Due to their weight, parasite eggs and cysts can be effectively settled in simple pre-treatment to avoid long term health risks originating from Helminth reaching the field (Crites et al., 2000).

Nutrients

Leaching of nitrogen in ground- or surface water poses the greatest risk for environmental contamination. Nitrogen is relatively mobile in soil water and leaches out fast. In groundwater it can result in quality problems for the use of groundwater as drinking water resource. Reaching surface water it can lead to eutrophication of water bodies.

"The removal of nitrogen in land treatment systems is complex and dynamic owing to the many forms of nitrogen (N_2, organic N, NH_3, NH_4, NO_2 and NO_3) and the relative ease of changing from one oxidation state to the next."(Crites et al., 2000:37) For risk evaluation it is important to know total concentration of nitrogen and the forms present (i.e., organic, ammonia, nitrates, etc.) in wastewater. Experiences in land treatment suggest that the less oxidized the nitrogen when applied on land; the more effective will be the retention and overall nitrogen removal (Crites et al., 2000).

The nitrogen circle in soil and environment is a complex process and will not be described exhaustively in this document. For in depths explanation consultation of Paul and Clark (1989) and Medigan et al. (2001) is suggested.

Possible microbial transformation processes of different forms of nitrogen in water and soil can be overlooked in Figure 5-7.

Organic nitrogen is mainly found in form of NH_2 in proteins and can be mineralized by micro organisms to ammonia. Ammonia is oxidized under aerobic conditions to nitrate (nitrification), whereas nitrate can again be reduced under anaerobic conditions stepwise to atmospheric nitrogen which is lost to the atmosphere (denitrification). Atmospheric nitrogen can be fixed by some microorganisms to ammonia (Madigan et al., 2001). Next denitrification and minor volatilization, crop uptake of nitrate and conversion into organic matter is the major pathway of Nitrogen removal from the plant-soil-water matrix.

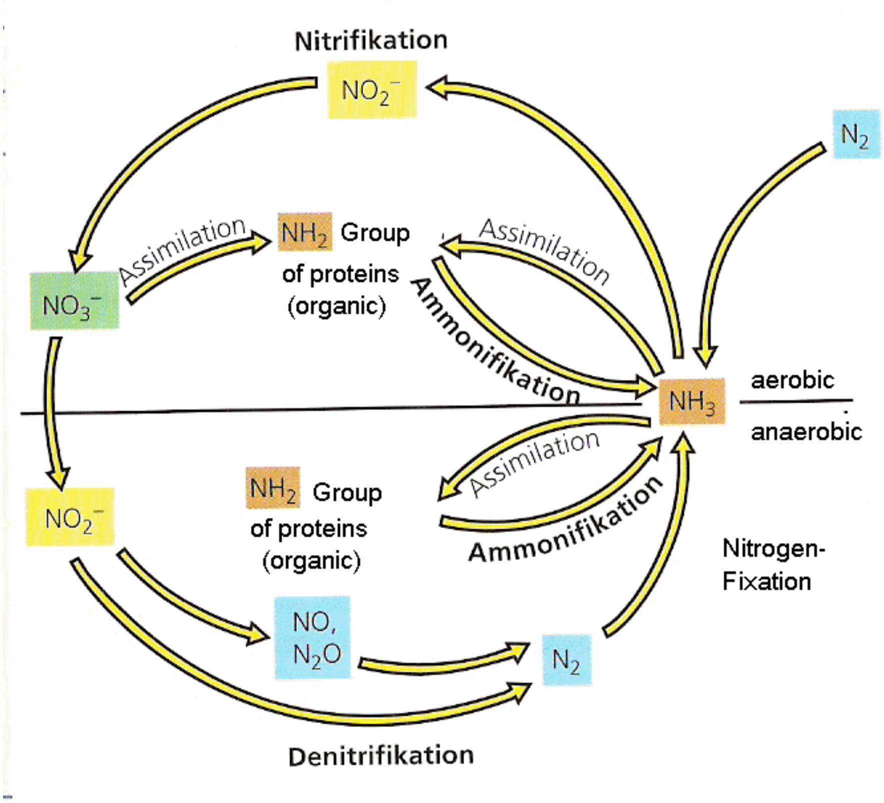

Figure 5-7: Microbial nitrogen transformations (Source: Madigan et al., 2001 (translated)).

"In soils, the ammonia ion is held on exchange complexes of the soil (e.g. of clay) and its movement into and through the soil water is thus greatly restricted, whereas the nitrate ion can move to the plant root either by diffusion or by mass flow with water." (Paul and Clark, 1989:159) Consequently nitrification is an essential process in evaluation of potential crop uptake and risk of nitrate leaching of total nitrogen applied. As presented in Figure 5-7 nitrification can only occur under aerobic conditions. Therefore it is necessary to allow periodic restoration of aerobic conditions by avoiding water logging during land application of water to allow nitrogen uptake by plants. In most cases this situation is apparent in agriculture since irrigation is not happening continuously and roots and macro organisms aerate the soil profile (Paul and Clark, 1989). Under optimal conditions, 67 kg/ha ammonia nitrogen can be converted to nitrate each day (Crites et al., 2000).

The organic N fraction usually associated with particulate matter is entrapped or filtered by the soil out of the applied liquid stream. Microbial decomposition of organic matter proceeds slowly and contained organic nitrogen is mineralized and released as ammonia. Jingguo and Bakken (1989) show that decomposition and mineralization of organic nitrogen is enhanced on planted land since plant roots have a positive effect on microbial decomposing activity.

The ammonia fraction of nitrogen in applied irrigation water can be lost by volatilization of ammoniac, adsorbed temporarily by clay minerals or transferred into nitrate and taken up by crops or lost to the atmosphere due to denitrification (Paul and Clark, 1989).

Possible pathways of nitrogen removal in agricultural soils are presented in Table 5-21, whereas the exact proportions are case and season specific.

Table 5-21: Nitrogen economy of soil (source: Paul and Clark, 1989:158).

Removals/losses	Range [%]
Crop uptake	0 - 60
Gaseous loss	0 - 30
Erosion	0 - 15
Immobilization	0 - 40
Leaching	0 - 10

The different chemical configurations of phosphates in wastewater have to be transferred to orthophosphate to be immediately bioavailable. In typical soils the necessary hydrolysis of polyphosphates proceeds very slowly. Phosphorus removal in soil can happen by plant uptake, biological, chemical, and/or physical processes. Long term experiences on land treatment systems for municipal wastewater prove that a removal of 99,9 % phosphorus on 1,5 m percolation depth is common(Crites et al., 2000).

In wastewater, potassium and other micronutrients are usually present but in terms of environmental and health risks harmless due to low concentrations (Crites et al., 2000).

Trace metals

The removal of metals in the soil is a complex process involving the mechanisms of adsorption, precipitation, ion exchange, and complexation. Adsorption of most trace elements occurs on the surfaces of clay minerals, metal oxides, and organic matter. As a result, fine-textured and organic soils have a greater adsorption capacity for trace elements than sandy soils (Crites et al., 2000).

In respect to metals, the major concern is the potential for accumulation in the soil profile and subsequent translocation, via crops or animals, through the food chain to man. The health risks of metals entering the food chain are not discussed in this study.

Any metals reaching the agricultural site with irrigation water that are not infinitely complexed in the soil profile or extracted by crops will leach eventually in the groundwater.

It is unlikely that metals from irrigation with domestic wastewater will cause a significant contamination to the environment. In industrial wastewater though they might become the limiting factor due to high concentrations and cause a groundwater contamination risk (Crites et al., 2000; Pettygrove and Asano, 1985).

5.2.3 Legal aspect relevant for irrigation with wastewater

<u>Department of Health (DoH): Guide: Permissible utilisation and disposal of treated sewage effluent, 1978</u>

The guideline stipulates the need for any use of treated effluent from domestic origin to comply with presented regulations which has to be certificated by the regional director of DoH.

The regulation is specific for different types of wastewater and wastewater treatment in combination with permissible crop types. Wastewater treatment pond effluent is specified as having a retention time of minimum 45 days and a maximum permissible microbial effluent quality of 10^3 *E.coli* / 100mL. The process combination of primary- (screening and settling), secondary- (biological filter bed process or activated sludge process), tertiary treatment (land treatment, maturation ponds and filtration or disinfection) is characterised as having an effluent quality complying with GENERAL STANDARDS specified in Governmental Notice R553 (1962) with the *E.coli* count relaxed to a maximum of 10^3 *E.coli* / 100mL. Wastewater treatment by a wastewater treatment pond or by the treatment sequence of primary, secondary and tertiary treatment is the minimum treatment requirement for permissible effluent irrigation of crops for human consumption not eaten raw. For fruit trees (fruits eaten raw) an exception is stipulated for the irrigation with flood, drip or micro irrigation to be allowed with the mentioned effluent (DoH, 1978).

To irrigate crops consumed raw by man a primary, secondary, tertiary and advanced purification ("special physico-chemical purification or other advanced techniques" (DOH, 1978:3)) (see Box 5) for wastewater is required, complying with SPECIAL STANDARD specified in Governmental Notice R553 from 1962 (DoH, 1978).

Definition of GENEARAL STANDARDS and SPECIAL STANDARDS as specified in Governmental Notice R553 (1962) were redefined in the Government Gazette No. 9225 (1984) (DWA, 1984).

Box 5: Definition of physicochemical purification source: [8]

Physicochemical purification is "Used to concentrate waste brines and to remove solid organics and ammonia from aqueous solutions. Physical treatment consists of reverse osmosis, dialysis, electro dialysis, evaporation, carbon adsorption, ammonia stripping, filtration, sedimentation, and flocculation. Chemical treatment consists of ion exchange, neutralization, oxidation, reduction, precipitation, and calcination." [8]

Governmental Gazette No. 9225, 18. 5.1984, Department of Water and Environmental Affairs (DWA)

In the Governmental Gazette No. 9225 treatment requirements for the purification of wastewater or effluent are enforced lawfully by the minister of Environment Affairs and Fisheries. Special and general standards are defined in the document and displayed in extract in Table 5-22 (DWA, 1984).

Table 5-22: Special and general standards for wastewater treatment (DWA, 1984).

	Fecal coliforme / *E.Coli* [CFU/100mL]	COD [mg/L]	TSS [mg/L]	Ammonia [mg/L-N]	Nitrate [mg/L-N]	Ortho phosphate [mg/L-P]	Residual Chlorine [mg/L-Cl]
General standard	0	75	90	1	Not specified	1	0,1
Special standard	0	30	10	1	1,5	1	0

Government Gazette No. 20526, 8.10.1999, Department of Water Affairs and Forestry (DWAF)

The governmental gazette is a lawful addition to the National Water Act from 1998 and counts for wastewater use as defined in Section 21(e) in a controlled activity such as irrigation (NWA, 1998).

The regulation stipulates that irrigation with domestic wastewater can be performed with up to 500 m³/d (without limitations on area) if the following water quality parameters are given:

- Electric conductivity < 2 dS/m;
- pH = 6 – 9;
- COD < 400 mg/l after removal of algae;
- faecal coliforms < 10^5 CFU / 100 mL

Additionally, irrigation is not permitted below the 100 year flood line and above a major aquifer. Next to project documentation, the user must take measures to avoid water logging and insect breeding, wastewater entering surface water, deterioration and damage of soil and the unauthorised use of wastewater by members of the public. If irrigation according to mentioned aspects is performed with more than 10m³/d the user has to register as such (DWAF, 1999).

5.3 Magabheni case study

In Magabheni two wastewater irrigation projects were carried out. The description of the first ‘disposal driven’ agricultural project which took place from 2003 till 2007 and the description of the design process of the second, ‘community driven’ farm system can be found in Appendix 9.5. The research at hand was written during and contributes to the second, ‘community driven’ system design. The written report focuses on the risk assessment of the proposed ‘community driven’ farm.

5.3.1 Proposed farm

The proposed farm is a 1 ha fenced plot planted with a large variety of locally consumed crops and is managed by five farmers. The proposed irrigation system comprises four operational storage tanks with a total capacity of 20 m^3 which enables farmers to withdraw water on the field on-demand from the gravity feed supply system. An electrical pump installed at the last Magabheni treatment pond can be operated to pump irrigation water from the pond into the operational storage tanks (approx. 2-3 times a week under maximum irrigation demand). The irrigation method is not decided on, even though furrow irrigation seems to be most appropriate since it is simple to manage and to maintain when using low quality water. Shortcoming of furrow irrigation is a high initial labour input. Based on cabbage as reference crop (justified in appendix 9.5), irrigation demand and expected irrigation water application can be calculated.

The various risks of the proposed farming system are evaluated based on background information given in the literature study, expected irrigation water requirements and monitored Magabheni pond quality and quantity.

5.3.2 Assessment of health risks

In this document the main focus lies on evaluation of microbial health risks for consumers of crops irrigated with treated wastewater. Potential health risks for farmers irrigating with wastewater are presented in Box 6.

Box 6: Potential health risks for farmers irrigating with treated wastewater.

The health risks for farmers result mainly through contact of contaminated water or soil with farmer's skin (feet, legs and hands). This can lead to rash and other skin infections (WHO, 2006). Secondary food handling and consumption with contaminated hands can lead to ingestion of pathogens. Protection wear and good hygienic praxis are expected to eliminate these health risks. The accidental ingestion of small amounts of contaminated soil and irrigation water is considered to be of minor risk and will not be further discussed. In this study, quantitative microbial risk assessment is not performed for health risks of farmers since personal protection measures will reduce risks to a minimum. The exposed group is very small and it is simple to raise awareness and understanding of potential health risks. In case a skin infection is occurring, farmers will know the reason immediately and be able to apply personal protection measures. This short feedback loop and internal control of the farmers community will eliminate serious health consequences for farmers irrigating with treated wastewater.

Evaluation of health risks for consumers of agricultural products is done with a Quantitative Microbial Risk Assessment (QMRA). As described in the literature study QMRA is a four step process. The first step consists of identifying the regional relevant hazardous microbial agents transmittable by irrigation with wastewater. WHO guidelines (2006) on wastewater use in agriculture recommend to collect background levels of faecal-oral disease in the population. Epidemic disease investigation in the area was not possible due to restrictions in data access for ethical reasons. In an interview at the Magabheni Clinic, serving the wastewater generating community, the physician stated that there was no case of cholera for many years. There are always some cases of diarrhoea in the area and all children between one and five years are treated prophylactic against worm infection (Pers. comm. physician Magabheni Clinic, Jul. 2009). Because of the insufficient analytical data base on expected diseases originating from the given wastewater, further evaluation relies on literature data to estimate the relevant infective agents.

Based on a literature review Soller et al (2004) identified pathogens present in reclaimed water and of public health concern. These are:

- Viruses: *Enteroviruses*, *Rotavirus*, *Caliciviruses*.
- Protozoan Parasites: *Cryptosporidium parvum, Giardia lamblia.*
- Bacteria: *Salmonella, Escherichia.coli* 0157:H7, *Shigella*." (Soller et al., 2004:4-3)

The used QMRA Monte Carlo simulation (Andrew Hamilton method) program can only process infection risks origin from *Rotavirus*, *Salmonella, Shigella* and *Campylobacter* are possible to be modelled since necessary modulation data are not available for other pathogens. For QMRA required disease to infection ratio and dose response factors for the chosen target pathogens are presented in Table 5-23.

Table 5-23: Pathogen dependent disease to infection ratio and dose response data from literature.

	Rotavirus[1]	Salmonella[2]	Shigella[2]	Campylobacter[1]
Disease/infection ratio	0,05	0.14-0.4	0.29-0.5	0,7
Dose response α	0,253	0.3126-0.89	0.21	Unknown

[1]source: WHO, 2006
[2]source: Soller et al., 2004

Since available analytical data on microbial organisms in the Magabheni treatment ponds are restricted to *E. coli,* it has to be used as single indicator organism. The use of indicator organisms is necessary to estimate the treatment efficiency of the pond system. On the basis of the treatment efficiency, the eliminated amount of pathogens from the initial concentration in raw sewage (Table 5-9), can be estimated Table 5-24.

Table 5-24: Estimation of microbial concentrations in raw sewage at Magabheni pond inflow based on literature data.

Organism	Concentration of organisms [MPN/100mL]
Total coliform	$10^7 – 10^9$
Faecal coliform	$10^6 – 10^8$
E.coli	$9 \cdot 10^6 – 10^8$
Shigella	$10^0 – 10^3$
Salmonella	$10^2 - 10^4$
Campylobacter	$10^{-1} – 10^3$
Vibrio cholerae	10^0
Rotavirus	$10^2 – 10^3$
Helminth ova	$10^0 – 10^3$
Protozoan cysts	10^4

Raw sewage is entering a four pond treatment system which is according to Varón and Mara (2004) the usually most appropriate method of domestic wastewater treatment in warm climate, developing countries. Wastewater treatment ponds are "low-cost (usually least-cost), low-maintenance, highly efficient, entirely natural and highly sustainable." (Varón and Mara, 2004:1)

In this document the treatment mechanisms of wastewater treatment ponds are not explained in detail, but for a better understanding of pathogen removal Table 5-25 provides an overview of relevant removal mechanisms.

Table 5-25: Factors proposed to cause or influence disinfection in wastewater treatment ponds (source: modified: Jenner, 2009)

Factor	Likely Mechanism	Microorganism affected
Temperature	Affects rate of removal processes	Bacteria, viruses, protozoa, helminth
Hydraulic residence time	Affects extent of removal	Bacteria, viruses, protozoa, helminth
Algal toxins	Toxic to some bacteria	Mainly bacteria
Sedimentation	Settlement of infectious agents or settlement of aggregated solids including infectious agent.	Protozoa, helminth, (viruses and bacteria)
Predation	Ingestion by higher organisms	Bacteria, viruses
Sunlight	DNA damage by solar UV-B radiation or photo-oxidation	Bacteria (protozoa)
pH, dissolved oxygen	Extreme variations of both parameters interact with other removal mechanisms and stress organisms	Bacteria, (protozoa)

From 2000 till 2009 *E. coli* concentrations were analysed at pond outfall in 83 almost monthly measurements performed by EWS. In 71 % of the samples no *E. coli* could be detected in 100 mL. The remaining 29 % showed results from 20 up to 6500 CFU/100 mL without any observable seasonal or historical pattern. The distribution of *E.coli* measurements can be seen in Figure 5-8.

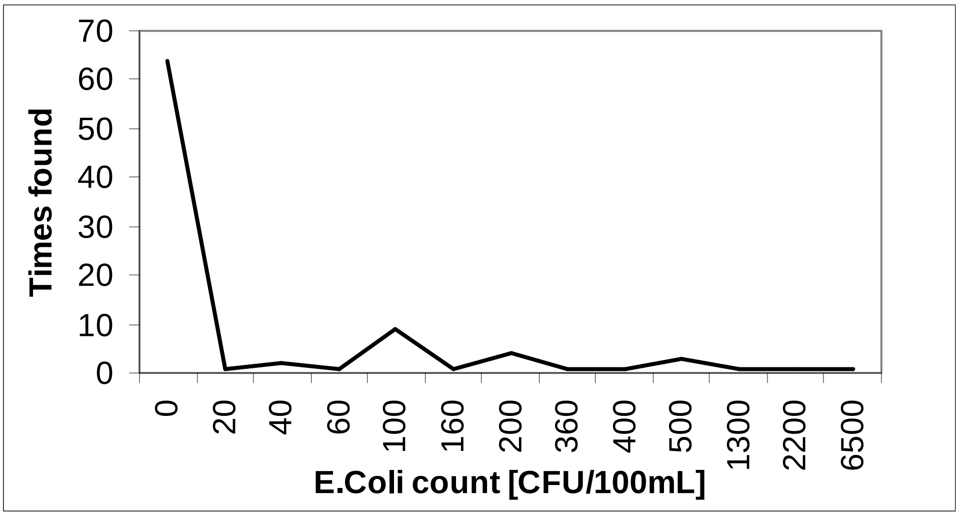

Figure 5-8: Distribution curve of *E. coli* concentration from analytical data of Magabheni pond outfall 2000 – 2009 analysed by EWS.

For the QMRA a conservative approach is taken and the assumption made that in the worst case 500 CFU/100 mL *E.coli* might be present in pond effluent. 500 CFU/100 mL were measured three times, whereas 1300, 2200 and 6500 CFU are not considered since they were only detected once in nine years and are considered to be outliers or mismeasurements.

Due to long hydraulic residence time of wastewater in the pond system the assumption is taken that all removal mechanisms (Table 5-25) for pathogens are highly effective. The *E.coli* reduction from assumed 10^6-10^8 MPN/100 mL at pond inflow to 500 MPN/100 mL at pond outflow implies a Log-unit reduction of 4 - 6 for bacteria which seems to be realistic regarding suggestions by WHO (2006) guidelines. The guidelines provide a list with Log-unit removals for pathogen groups by wastewater treatment processes. For wastewater treatment ponds the given values are:

- viruses: 1 – 4
- bacteria: 1 – 6 “ (WHO, 2006: 81)

Considering these Log-unit reductions it was chosen to assume log reductions as follows:

- viruses: 3
- bacteria: 5

Subsequent, microbial quality of pond effluent can be calculated (Table 5-26) based on raw sewage quality provided in Table 5-24.

Table 5-26: Calculated microbial parameters of pond effluent.

Organism	Concentration of organisms [MPN/100mL]
Total coliform	$10^2 – 10^4$
Faecal coliform	$10^1 – 10^3$
E.coli	$9 \cdot 10^1 – 10^3$
Shigella	$10^{-5} – 10^{-2}$
Salmonella	$10^{-3} – 10^{-1}$
Campylobacter	$10^{-6} – 10^{-2}$
Vibrio cholerae	10^{-3}
Rotavirus	$10^{-1} – 10^0$

Wastewater treatment ponds with slow flow rates and long hydraulic residence times are very efficient for sedimentation of comparable large and heavy helminth eggs and protozoan cysts. Several studies prove a complete removal of protozoan cysts and particular helminth eggs (e.g. *Ascaris*) (compare Figure 5-9) with maximal hydraulic retention times in treatment ponds of 20 - 40 days (Amahmid *et al*., 2002; Jenner, 2009; Sperling *et al*., 2005). Regarding the calculated hydraulic retention time in the Magabheni pond system of over 110 days the author assumes that in pond effluent no protozoan cysts and helminth eggs can be found. Only viruses and bacteria will be considered for the further assessment of health risks which is performed according to the scheme presented in appendix 9.1.

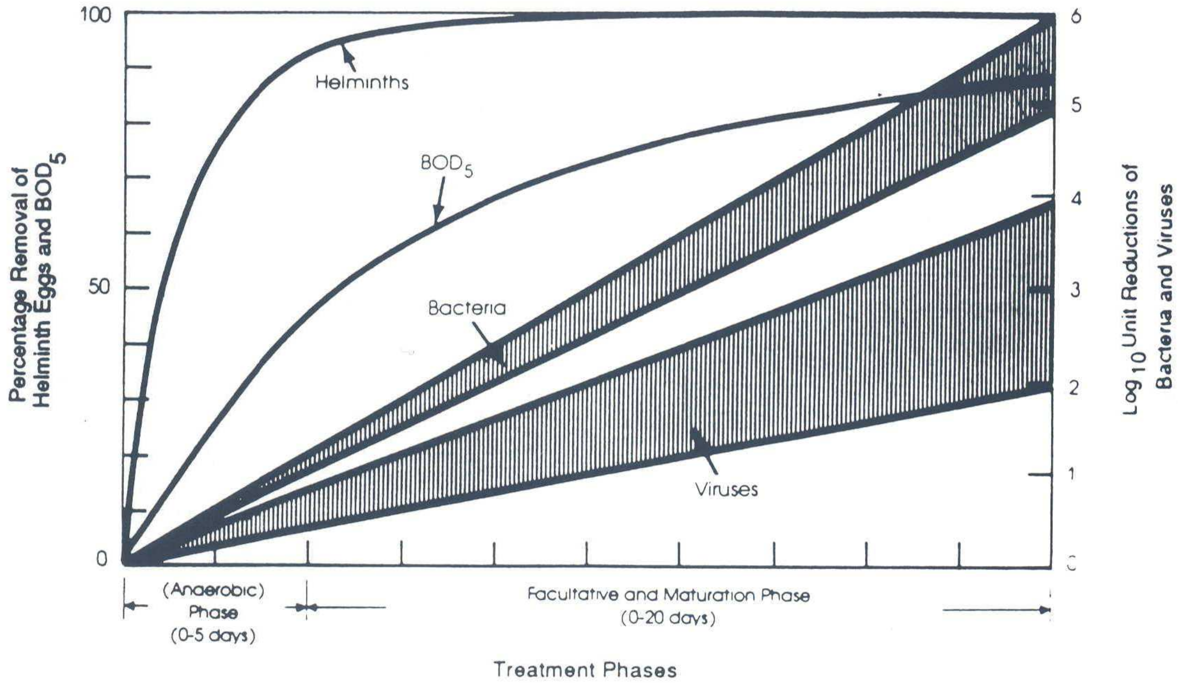

Figure 5-9: Generalized removal curves for BOD, helminth eggs, excreted bacteria, and viruses in waste water treatment ponds at temperatures above 20℃ (L ibhaber, 2009:12).

After wastewater treatment in the pond system, effluent is being pumped into the four operational storage tanks. The tanks of 5 m³ each, are closed (not air tight), nontransparent plastic vessels and during irrigation season water remains in them for approximately 2 – 4 days as investigated in research presented in appendix 9.5. No UV-light will have any reduction effect on microorganisms. Also algae, which might be transported from the pond system into the tanks, will not be able to carry out photosynthesis. Since the outtake of the storage tanks is on the very bottom and sedimentation mechanisms will have happened excessively in the treatment ponds, also no pathogen reduction by sedimentation is expected. Due to short retention times in the tanks in comparison to the treatment ponds, no re-growth of bacteria is expected.

The next steps for determining health risks for consumers of agricultural products is to define the amount of pathogens in irrigation water reaching (and remaining on) the crop. The determining aspects are irrigation system, volume of water applied by irrigation, agricultural practice and crop type (appendix 9.1).

All four factors are connected with each other. The QMRA calculation is performed for the chosen reference crop cabbage for the period of the year with maximum irrigation requirements. Due to later described time dependent pathogen die-off by environmental decay, the total amount of applied irrigation water over the whole growing period is relatively irrelevant for microbial risk evaluation for viruses and bacteria. For this study a focus is put on the last two weeks of irrigation before harvest. Table 9-4 encompasses maximum irrigation water demand of cabbage before harvest if no rain is occurring. On the basis of estimated 0,7 irrigation water application efficiency for sprinkler and 0,6 for furrow irrigation (justified Table 9-6) the resulting maximum daily applied water per head of cabbage can be calculated (Table 5-27) (size and weight of cabbage justified in appendix 9.5).

Table 5-27: Conservative approach of applied irrigation water in the last two month before harvest without rainfall.

Month [two weeks]	Jul I	Jul II	Aug I	Aug II
Sprinkler: applied irrigation water per head of cabbage [L/day]	0,557	0,643	0,729	0,776
Furrow: applied irrigation water per head of cabbage [L/day]	0,650	0,750	0,850	0,905

Exact values of remaining water and pathogens on crops relative to a used irrigation methods are not readily available in literature for QMRA (Hamilton et al., 2005) as discussed in the literature study.

To evaluate the irrigation system in terms of resulting health risks for consumers an exposure assessment is carried out for irrigation with furrows and sprinklers.

The following calculation attempts to analyse the expected amount of pathogens on plant surface originating from polluted irrigation water. Assumed accumulative effects by continues daily irrigation and natural die off ratios will be analysed in order to draw conclusions for possible on-farm management responses to health risks.

For the calculation the assumption is taken that applied irrigation water by sprinkler irrigation will come to 100 % in contact with crop surface. A maximum of 5 % of applied irrigation water in furrows is assumed to come in contact with crop surface. The conservative approach for furrow irrigation accounts for small amounts of wastewater contaminated dust, soil, or splash water reaching the plant surface.

Furthermore it is assumed that 90 % of the irrigation water reaching the plant will roll off the surface immediately. The remaining 10% of irrigation water on plant surface is assumed to evaporate and leave the analogous amount of pathogens on plant surface. For this exemplary calculation, *E.Coli* is used as indicator with an assumed concentration of 1000 MPN/100mL irrigation water (simplification from Table 5-26). The calculation of above described assumptions can be found in Table 5-28.

Table 5-28: Remaining contaminated irrigation water on each head of 2 kg cabbage directly after irrigation.

Irrigation Method	Applied water per head [L/day]	Water in contact with head [L/day]	Remaining irrigation water on plant [L/day]	*E.Coli* remaining on plant surface [MPN/Cabbage]
Sprinkler	0,776	0,776	0,077	776
Furrow	0,905	0,045	0,005	45

To model the amount of pathogens remaining on plant surface after irrigation over several days, two assumptions are taken:

- Once pathogens are on the plant surface they will not be washed off by following irrigation or rain events (compare literature study). This implies that the amount of pathogens remaining on plant surface will accumulate over the irrigation days to 100%.
- Pathogens on plant surface are dying off by environmental decay.

The environmental decay of pathogens on plant surface will be calculated according to the decay function (Equation 4) which describes an exponential time dependent decay of pathogens on plant surface.

Figure 5-10 presents the amount of remaining viable *E.Coli* on each head of cabbage for successive daily sprinkler and furrow irrigation. The presented pathogen numbers are a product of accumulative effects and environmental decay.

The accumulative effect alone would simply create a straight line with the slope of daily irrigation water (pathogens) added and remaining on the plant. The reason that the graphs levels out is that, the longer pathogens remain on plant surface, the more die-off (exponentially) by environmental decay.

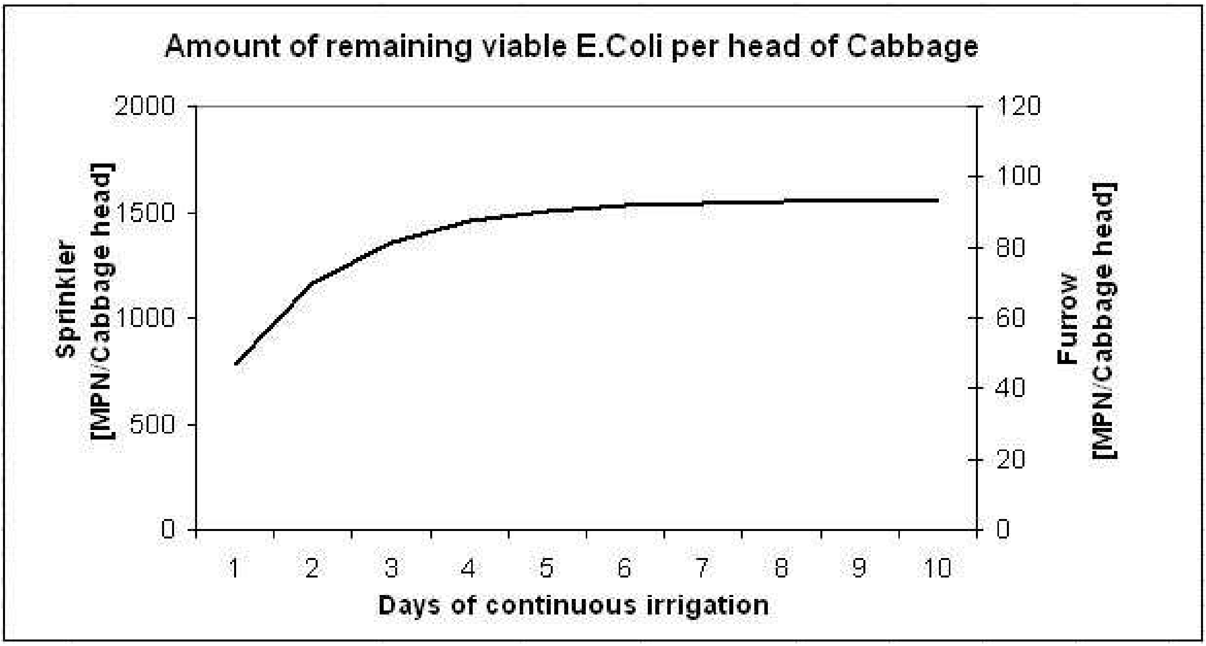

Figure 5-10: Modelled amount of *E.Coli* per head of cabbage over a period of 10 days successive irrigation by furrow and sprinkler irrigation.

WHO (2006) guidelines on wastewater use in agriculture suggest that stopping irrigation before harvest allows an effective Log-unit reduction of viable pathogens. This can be confirmed in Figure 5-11 by modelling the successive decay of pathogens when irrigation is stopped. For the calculation an initial amount of viable pathogens after 12 days successive irrigation (as calculated above) is assumed as starting condition. On the x-axis of the presented figure, the number of days irrigation stops before harvest are plotted.

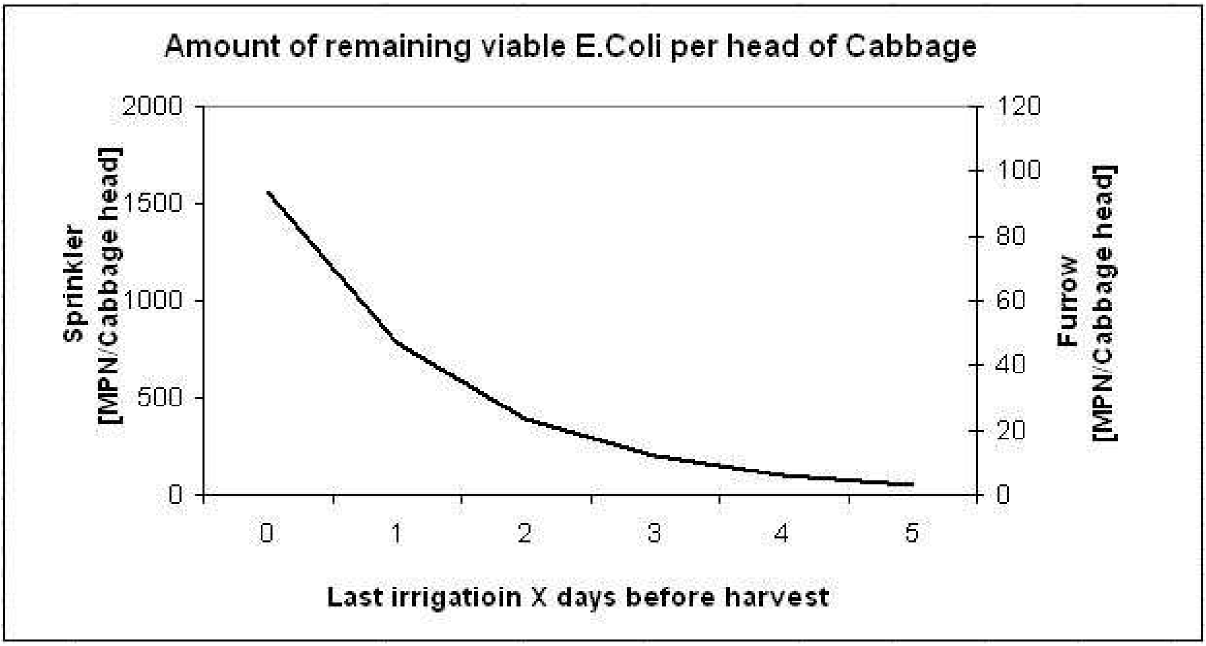

Figure 5-11: Modelled amount of pathogens per head of cabbage when irrigation is stopped X days before harvest after a period of 12 days successive irrigation for furrow and sprinkler irrigation.

Estimated amounts of the indicator pathogens on cabbage are an input for calculation of the annual risk of infection (P_I) for the pathogens of interest by using the Microsoft Excel based QMRA –Monte Carlo program for wastewater use in agriculture provided by Professor Mara from the University of Leeds.

The program (interface presented in appendix 9.3) works with macros and uses the ß-Poisson dose-response equation for viral and bacterial pathogens also used by WHO (2006). The program calculates the median and 95-percentile annual infection risk from consuming every *n* days an approximate quantity of cabbage with attached pathogens origin from irrigation with water of a specific quality. Required data need to be fed in the model in ranges and output data are produced by *1000-Monte Carlo* random generator simulation to reach a certain statistical certainty (Mara, D., 2008).

Table 5-29 shows the required input parameters with selected data.

Table 5-29: Input parameters with chosen values for QMRA-MC *Unrestricted Irrigation 2* program provided by Mara, D.

Input parameter	Chosen Value
Faecal coliforms per 100 mL	Calculate from Table 5-26
Pathogen numbers per 10^5 faecal coliforms	Calculate from Table 5-26
Volume of wastewater remaining on 100 g cabbage after irrigation [mL]	Transformed data from Figure 5-11
Quantity of cabbage consumed on each occasion [g/d]	30 – 50 g [1]
Pathogen die-off between last irrigation and consumption; if any [Log-units]	0
Consumer exposure (consumption of wastewater irrigated crops every *n* days)	2 – 4 [1]
Pathogen specific disease/infection ratio	Pathogen specific maximum Table 5-23
Variation from default value (+/- %) for pathogen coefficients	25% is given as default
N_{50} for pathogen coefficients	Pathogen specific default is used
Alpha for pathogen coefficients	Table 5-23, pathogen specific default for *Campylobacter*

[1]During all household interviews within the community around the Magabheni community garden site the question was posed how often raw vegetables or salads are consumed. 8 of the 20 households responded that they eat cabbage, tomatoes, carrots and onions raw in form of salad as side dish for dinner. On the question in what frequency these salads are consumed the most frequent consumption was 2-3 times a week by 3 households. The assumption is made that a cabbage salad as side dish contains maximum 50 g of cabbage per person.

Alpha (α) and N_{50} are input values for the β-Poisson equation which is used to calculate the annual risk of infection. The equations used by the program and also in the WHO (2006) guidelines are formally developed by Professor Hillel Shuval and presented underneath.

β-Poisson dose-response model:

Equation 5

$$P_I(d) = 1 - \left[1 + \left(\frac{d}{N_{50}}\right)\left(2^{1/\alpha} - 1\right)\right]^{-\alpha}$$

Annual risk of infection:

Equation 6

$$P_{I(A)}(d) = 1 - \left[1 - P_I(d)\right]^n$$

With:

$P_I(d)$ = risk of infection in an individual exposed to a single pathogen dose *d*

$P_{I(A)}(d)$ = annual risk of infection in an individual from *n* exposures per year to the single pathogen dose *d*

N_{50} = median infective dose

α = pathogen “infective constants” (Mara, 2008).

The calculated annual risk of infection for *Salmonella, Shigella, Campylobacter* and *Rotavirus* per person per year (pppy) resulting from irrigation with treated wastewater in Magabheni is displayed in Table 5-30. The infection risk is calculated for sprinkler and furrow irrigation and the scenarios that last irrigation is happening on the day of harvest and respectively 1, 2, 3 and 9 days before harvest.

Table 5-30: Calculated annual risk of infection for *Salmonella, Shigella* and [*per person per year] (E x=10^x^).*

Irrigation stopped x days before harvest [day]	0	1	2	3	9
Annual risk of infection for *Salmonella* [pppy]					
Sprinkler	8,5E-05	4,3E-05	2,2E-05	1,1E-05	1,5E-07
Furrow	5,1E-06	2,5E-06	1,3E-06	6,4E-07	1,0E-08
Annual risk of infection for *Shigella* [pppy]					
Sprinkler	7,9E-04	4,0E-04	2,0E-04	1,0E-04	1,4E-06
Furrow	4,7E-05	2,3E-05	1,2E-05	5,8E-06	8,0E-08
Annual risk of infection for *Rotavirus* [pppy]					
Sprinkler	1,0E+00	9,9E-01	9,1E-01	7,1E-01	1,8E-02
Furrow	4,4E-01	2,6E-01	1,4E-01	7,1E-02	1,0E-03
Annual risk of infection for *Campylobacter* [pppy]					
Sprinkler	3,6E-03	1,8E-03	8,8E-04	4,5E-04	6,1E-06
Furrow	2,1E-04	1,0E-04	5,3E-05	2,6E-05	3,6E-07

Regarding the annual risk of infection, it is obvious that the infection risk posed by *Rotavirus* is the highest. This finding is in line with the epidemiologic study on the burden of disease performed by Havelaar and Mels (2003) in preparation of the WHO guidelines on drinking-water quality. “*Rotaviruses* are the single most important etiologic agents of severe diarrheal illness of infants and young children world - wide.”(Havelaar and Mels, 2003:34) Also the WHO (2006) shows that diarrhea has worldwide the highest mortality and DALY rates of all diseases of relevance in regard to wastewater use in agriculture. 99,8 % of diarrhea deaths occur in developing countries and 90% of diarrhea death occur amongst children (Havelaar and Mels, 2003).

To find tolerable pathogen specific infection risks, intense epidemiological studies have to be carried out as seen in Havelaar and Mels (2003) for *Rotavirus*. This elaborated calculation is not performed in this research, but the tolerable infection risk per person per year [pppy] based on the DALY threshold of 10^{-6} provided in WHO (2006) is used. Unfortunately the required data could only be found in literature for *Rotavirus* and *Campylobacter* as presented in Table 5-31. Due to the lack of data for evaluation of presented annual infection risks (Risk characterization) for *Salmonella* and *Shigella,* these pathogens will not be discussed further. As indicated in Havelaar and Mels (2003) a ‘development country’ and ‘developed country’ set of disease burden data is available for *Rotavirus*. For this research the scenario for development countries was chosen, since the target community is poor and the physician of the local clinic stated that diarrhea infections are frequent.

Table 5-31: DALYs, disease risks and tolerable infection risks for *Rotavirus* and *Campylobacter* (source: WHO, 2006:61 modified).

Pathogen	DALYs per case of disease	Disease risk pppy equivalent to 10^{-6} DALY [pppy]	Tolerable infection risk [pppy]
Rotavirus	2,6 E -2	3,8 E -5	7,7 E -4
Campylobacter	4,6 E -3	2,2 E -4	3,1 E -4

Comparing output data from Table 5-30 and guidelines on tolerable infection risk from Table 5-31 for *Rotavirus* and *Campylobacter* reveals the health risks for the intended farming system. In Figure 5-12 and Figure 5-13 is visualized that applying furrow irrigation in Magabheni is a measure to reduce health risk significantly. Furrow irrigation is an appropriate measure to reduce health risks from *Campylobacter* for consumers on the tolerable level suggested by WHO (2006).

For *Rotavirus* the resulting health risks has to be seen more critical. Only stopping irrigation 10 days before harvest, would allow a sufficient die-off of pathogens in a furrow irrigated system to achieve acceptable crop quality.

Allowing a long die-off period before harvest without irrigation is a strategy, risky to be violated by farmers. After 10 days without irrigation dehydration effects on the crop might become visible and harvest weight could be reduced resulting in decreased marketability (Pers. comm. F. Huibers, Irrigation and Water Engineering Group, Wageningen University, Jan. 2010). To apply an additional intervention step to reduce health risk in production or crop handling seems to be more promising. The required Log reductions for different possible scenarios to reduce annual risk of infection on the recommended level of $7{,}7 \cdot 10^{-4}$ are presented in Figure 5-14.

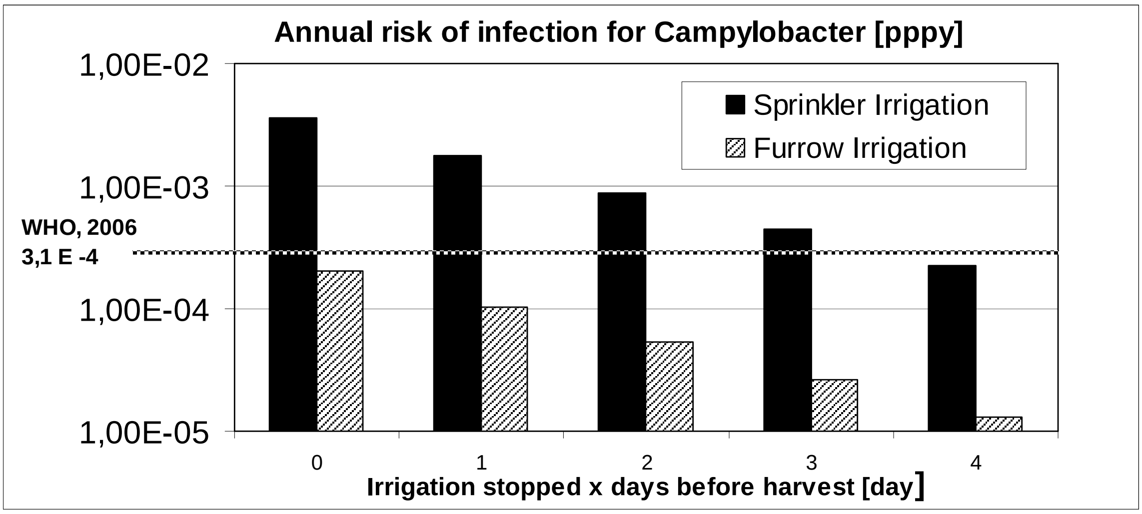

Figure 5-12: Modelled scenarios of annual risk of infection for *Campylobacter* [pppy] and the tolerable infection risk according to WHO (2006) (E x = 10^x).

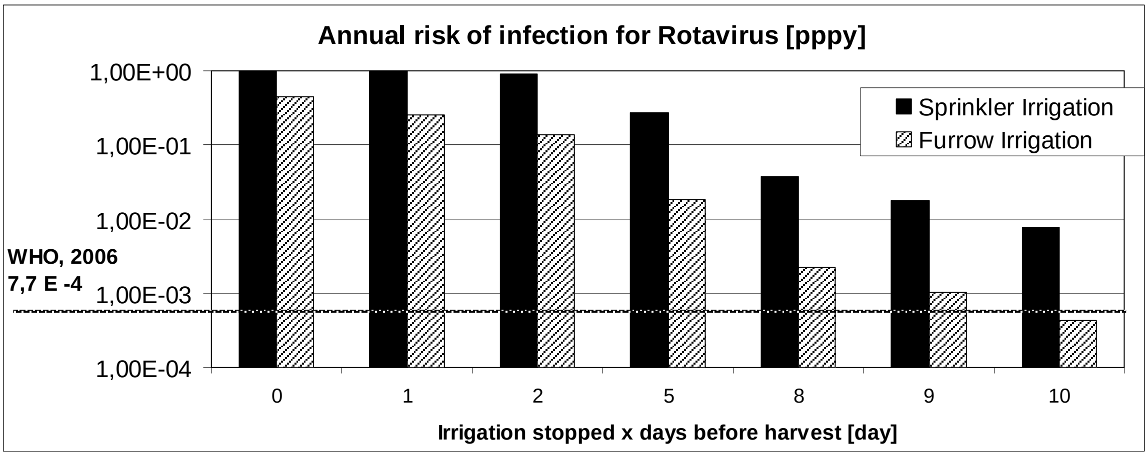

Figure 5-13: Modelled scenarios of annual risk of infection for *Rotavirus* [pppy] and the tolerable infection risk in development countries according to WHO (2006) (E x=10^x).

In the text above the influence of stopping irrigation before harvest on resulting health risks for consumers is elaborated.

Stopping irrigation before harvest is only one of many strategies to reduce health risks. The required additional Log-unit reductions of *Rotavirus* to meet health based targets according to WHO (2006) are presented in Figure 5-14 for the following four selected scenarios:

- Reduce pathogens about three Log-units and not stop furrow irrigation before harvest.
- Reduce pathogens about four Log-units and stop sprinkler irrigation one day before harvest.
- Reduce pathogens about two Log-units and stop furrow irrigation three days before harvest.
- Reduce pathogens about one Log-unit and stop furrow irrigation a week before harvest.

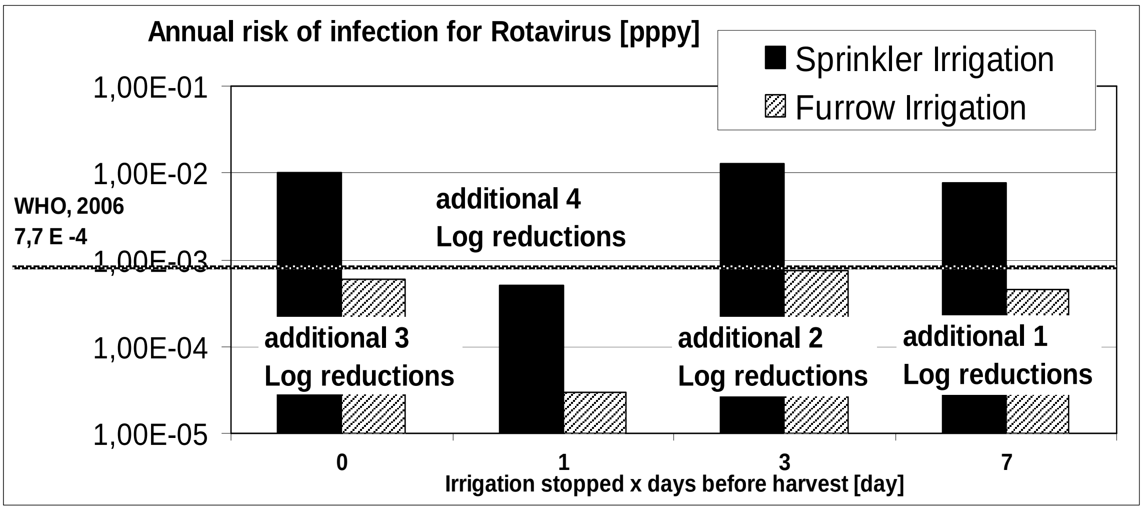

Figure 5-14: Minimal necessary additional pathogen Log-unit reductions required to reduce annual risk of infection for *Rotavirus* for scenarios meeting the tolerable risk of infection recommended by WHO (2006) (E x=10^x).

Conclusion

The detailed assessment of microbial health risk for consumers of agricultural products was performed on basis of cabbage as a potential worst case reference crop by using a Quantitative Microbial Risk Assessment (QMRA). The production chain of growing crops under effluent irrigation was modelled and resulting health risks were evaluated by using WHO (2006) Guidelines on wastewater use in agriculture. The model illustrates the good treatment performance of the Magabheni pond system on potential pathogens and the health risk reduction of furrow irrigation in comparison to sprinkler irrigation. Furthermore it was presented that stopping irrigation before harvest can reduce health risks for consumers of agricultural products effectively due to environmental decay. Nevertheless resulting crop contamination of raw consumed cabbage with *Rotavirus* was approximately three Log-units too high to comply with health based targets suggested by WHO (2006).

Evaluation of health risks for consumers of agricultural products irrigated with treated wastewater in Magabheni community gardens was done on basis of cabbage as worst case reference crop. Underground grown root crops consumed raw and potentially unpeeled (carrots) might pose an even higher health risk to consumers. WHO (2006) indicates that viral inactivation time on carrots can be far higher than on other crops. Due to limited scope of the research underground grown, raw consumed crops are not part of this study and suggested to be restricted to grow at the Magabheni site.

5.3.3 Risks for the agronomic system

In this document, evaluation of feasibility of given pond effluent quality for irrigation in terms of risks for the agronomic system is mainly done on base of FAO guidelines for water quality for agriculture (Ayers and Westcot, 1989). Additionally, literature data on irrigation water quality and guidelines for trace elements in irrigation water provided by Pettygrove and Asano (1985) will be used.

Guideline values from the FAO for irrigation water quality (introduced in Table 5-17) and additions made by Pettygrove and Asano (1985) (Table 5-18) are compared with data from Magabheni pond effluent in Table 5-32.

Table 5-32: Evaluation of measured and assumed Magabheni effluent quality for the use in agriculture on base of FAO guidelines and irrigation water quality suggestions in literature.

Parameter	Effluent quality	Guideline value	Evaluation
FAO guidelines for water use for agriculture (Ayers and Westcot, 1989)			
Conductivity[dS/m]	0,6 (long term survey, Table 5-2)	< 0,7	No restriction
TDS [mg/L]	380 (literature data, Table 5-8)	< 450	No restriction
Infiltration [SAR]	3,3 (intense survey, Table 5-3)	3 – 6 and Conductivity 1,2 – 0,3	Slight to moderate restriction on use
Sodium (Na) [SAR]	3,3 (intense survey, Table 5-3)	3 – 9	For surface irrigation: Slight to moderate restriction on use
Sodium (Na) [me/L]	3,48 (intense survey, Table 5-3)	> 3	For sprinkler irrigation: Slight to moderate restriction on use
Chloride (Cl) [me/L]	2,17 (intense survey, Table 5-3)	< 3	For sprinkler and surface irrigation no restrictions
Boron (B) [mg/L]	0,2 (literature data, Table 5-8)	< 0,7	No restriction
Nitrogen (NO_3-N) [mg/L]	3,5 (intense survey, Table 5-3)	< 5	No restriction
Total-N [mg/L][1]	8,3 (long term survey, Table 5-2)	5 – 30	Slight to moderate restriction on use
Bicarbonate (HCO_3) [me/l]	1,6 (literature data, Table 5-8)	1,5 – 8,5	For overhead sprinkling only: Slight to moderate restriction on use
pH	7-10 (long term survey, Table 5-2)	Norm: 6,5 – 8,4	Occasionally very high
Common irrigation water quality (Pettygrove and Asano, 1985)			
Calcium (Ca) [mg/l]	22 (intense survey, Table 5-3)	0 – 400	Normal range
Magnesium (Mg) [mg/l]	14 (intense survey, Table 5-3)	0 – 60	Normal range
Sulphate (SO_4) [mg/l]	35 (intense survey, Table 5-3)	0 – 1000	Normal range

[1]FAO Guidelines do not consider Total-N but only Nitrogen-N. Pettygrove and Asano (1985) suggest using Total-N instead of Nitrogen-N with the argumentation that all forms of Nitrogen can be transformed in other ones by microbial activity.

The performed evaluation of water quality for irrigation shows that irrigation with Magabheni pond effluent is feasible.

FAO guidelines were developed to assure full yield potential for all crops with no need for any special management if parameters meet the category “no restriction in use”. Nevertheless it is important to note that the made divisions of categories are not based on clear-cut breaking points and changes of 10 to 20 percent above or below a guideline value have little significance if considered in proper perspective with other factors affecting yield (Ayers and Westcot, 1989). Besides of total-N which is not included in the original guidelines and pH which is not formulated as guideline but only as indicator; if considering a 15% variance all other parameters would fall under the category “no restriction in use”. Furthermore, the guidelines are developed for semi-arid to arid climates where rainfall is low and does not play a significant role in meeting crop water demand or leaching requirements (Ayers and Westcot, 1989). In the Magabheni effluent irrigation project irrigation supplies maximal 50% (two month of the year) of the total crop water requirements (Table 9-3). The in Ayers and Westcot (1989) recommended leaching fraction of 0,15 for salt control is exceeded by a calculated leaching fraction of 2,4 for furrow irrigation under full plantation for the Magabheni case. The above discussed parameters, but particular salt content, in irrigation water have long term effects on crops and soil, which is eliminated by frequent precipitation and leaching. The climatic conditions allow the conclusion that salinity (sodium and conductivity) respectively SAR are no issue in Magabheni and no special management considerations have to be taken. Comparison of Magabheni effluent quality with South African quality guidelines for irrigation (DWAF, 1996b) presented as extract in appendix 9.2, suggests Magabheni pond effluent quality, besides of the high pH, as good to very good suitable for agricultural use.

The detected occasional high pH is assessed by Ayers and Westcot (1989) to be an indicator for further evaluation. High pH poses risks of nutritional imbalances, risk of foliage damage or may contain toxic ions. However changes in soil pH will take place very slow since the soil is strongly buffered. The greatest direct hazard of an abnormal pH in water is the impact on irrigation equipment (e.g. sprinklers) (Ayers and Westcot, 1989). Regarding the Magabheni case where furrow irrigation is intended to be used this might be a minor problem.

The contextual interpretation of high pH leads to characteristics of the pond treatment system. Treatment mechanisms particular of the facultative and maturation ponds are strongly linked to development of ample algae populations in the water (Jenner, 2009; Varón and Mara, 2004). Green algae in ponds are so called primary producers that conduct photosynthesis. With sunlight as energy source, green algae assimilate inorganic carbon (CO_2) from which they build up biomass (organic carbon) and excrete the remaining oxygen as waste product. Inorganic carbon in water has different configurations which are interconnected in a complex pH dependent equilibrium (calcite and carbonic acid equilibrium) (Rohmann, 1993). Green algae extract dissolved carbon dioxide for photosynthesis. In case of high photosynthesis rates given in wastewater treatment ponds, the reservoir depletes fast since atmospheric carbon dioxide has slow kinetics for dissolution in water. Consequently bicarbonate is used as carbon source for primary production. Organisms use the CO_2 and leave hydroxide ions (OH^-).

$HCO_3^+ \rightarrow CO_2$ for photosynthesis $\rightarrow$ organic carbon + OH^- (Gunkel, 2005).

Increased hydroxide ion production abstracts protons from the calcite and carbonic acid equilibrium which presses the equilibrium to supply more protons. This process is increasing the pH. Since photosynthesis is only happening during the day when the sun is shining, diurnal pH variations up to pH 10 in water bodies with high primary production are common (Gunkel, 2005). The management intervention for the pH problem is under considerations of the context simple. Farmers should pump water from the pond system in the early morning hours into their operational water storage tanks. The pH of water should be in a normal range in the early morning before photosynthesis starts. Since storage tanks are closed no sunlight will enable algae to increase pH in the tanks.

Evaluation of nutrients in pond effluent shows that the concentrations for nitrogen are rather high if the sum of all nitrogen configurations is considered. Analytical results of the long term study indicates that with 7 mg/L – N Ammonia and 1,3 mg/L – N Nitrate the proportion of the reduced, not readily crop available form of nitrogen is much higher than the directly bio available one. For this reason the effluent evaluation of feasibility for irrigation on basis of nitrogen-N in Table 5-32 is categorized with "no restrictions on use". Supplied ammonia will be adsorbed from the soil in Magabheni with high clay content. Soil microorganisms will convert ammonia to nitrogen and make it available over a long period of time. Is the field planted over the whole year with crops, nitrogen will be absorbed all year long.

Phosphorus in effluent is to 70% found in forms of plant available ortho-phosphate. The overall concentration of phosphorus in effluent is with 1 mg/L – P relatively low and total supplied phosphorus will become plant available eventually. Organic phosphorus will be degraded slowly to ortho-phosphate. According to Table 5-8 approximately 15 mg/L potassium might be expected in pond effluent.

Evaluation of the total amount of delivered nutrients in comparison to recommended fertilizer input in Germany over the year under full plantation is shown in Table 5-33. The estimation is based on planted cabbage in two growing seasons (March - August and September – February with respectively two weeks time between harvest and plantation) per year. The total amount of crop water requirements are combined with an assumed field application efficiency of 0,6 for furrow irrigation. The total applied irrigation water per year is 1411 m³/ha. Assuming the given effluent water quality for the supplied amount yields in the total nutrient input per ha displayed in the table underneath.

Table 5-33: Nutrients delivered by irrigation in Magabheni and nutrient requirements based on Niesel-Lessenthin (1988).

Nutrients	Delivered with irrigation	Requirements (from Table 5-19)
Total Nitrogen-N [kg/ha·year – N]	12	300
Total Phosphorus [kg/ha·year – P]	1	300
Potassium [kg/ha·year – K]	21	150

The presented data show that supplied nutrients by irrigation water are by far insufficient to meet fertilizer requirements. Regarding the fact that water applied through irrigation accounts to only 14 % of the total water reaching the field (precipitation + irrigation = 10281 m^3/ha·year) reveals that nutrient content in irrigation water is too small to provide enough fertilizer. This evaluation shows that negative effects on crops by over fertilization from nitrogen (which will be released slowly since applied mainly in ammonia) as indicated in Table 5-32 are unrealistic. Organic or mineral fertilizer application or plantation of legume crops for nitrogen fixation might be recommendable to enhance yields by extended nutrient availability.

The relatively small amount of organic substances in form of COD and suspended solids Table 5-2 reaching the field are not expected to pose a problem for the agronomic system. Organic substances are rather thought to enhance soil quality for various reasons presented in Table 5-20 and might incorporate some of the above discussed nutrients. Suspended solids might pose risk of clogging to irrigation infrastructure like sprinklers, drippers, or subsurface irrigation. The intended irrigation method with furrows is feasible for high amounts of suspended solids.

<u>Conclusion</u>

Evaluation of risks for the agronomic system from irrigation with Magabheni pond effluent in the intended manner could be proven to be insignificant. It was presented that risk for agronomic productivity is caused mainly from long term accumulation of specific substances in soil. On a yearly base, the amount of irrigation water in comparison to rain water reaching the field is very small (14%) which guarantees a high dilution of effluent constituents on site. Relative low concentrations of critical parameters in irrigation water due to good treatment performance of the pond system and its dilution over the year result in the possibility of irrigation as intended without any special managerial considerations. The evaluation of nutrients applied with irrigation water shows that on a yearly base, irrigation with effluent can only provide an insignificant proportion of total fertilizer requirements for the Magabheni agricultural site.

Occasional high pH values were identified as peculiar but could be linked to diurnal pH variations in treatment ponds due to photosynthesis activity of algae.

5.3.4 Risks for environmental pollution

The threat of environmental contamination resulting from irrigation with effluent from the Magabheni wastewater treatment ponds will be evaluated in the following. Initially it should be noted that for the case of Magabheni, irrigation with the given effluent was initiated as a post treatment step since formerly effluent was discharged directly in the *Ngane* river. Any kind of ground passage has a potentially net beneficial effect on percolating water, if no external contaminants are added from the agricultural site (for example pesticides of excessive mineral fertilizers).

Quality parameters measured in Magabheni effluent as presented in subchapter 5.1.3 will be evaluated step by step by comparison with findings from the literature study.

As developed earlier, the total applied irrigation water per year represents only 14 % of total water reaching the field and amounts 1411 m^3/ha. This results in hydraulic loading rates for irrigation water of only 141 mm/year and 1,4 mm/day in the period with maximum irrigation water requirements. Comparing these values with hydraulic loading rates in slow rate land treatment systems of 0,6 – 6,0 m/year it is expected that the environmental contamination risk by added contaminants in Magabheni is negligible.

Organic loadings indicated by COD concentration in Magabheni wastewater treatment ponds was found to be in average 84 mg/L. Due to the analytical method, COD is always higher then BOD_5 (Metcalf and Eddy, 2003) and will in such low concentrations not pose a risk to the hydraulic system of the soil nor the groundwater. Crites et al. (2000) present examples where BOD_5 with concentrations of 92 mg/L were removed to over 98% in a 1,5 m ground passage with hydraulic loading rates of 7,6 m/year.

Crites et al. (2000) also evaluated total suspended solids with typical loadings in wastewater of 120 mg/L as to be no issue in land application. The detected 41 mg/L in the Magabheni case are far lower than the mentioned value.

For pathogen removal by ground passage, values from pond outfall (Table 5-26) can be assumed as input parameters. Crites et al. (2000) suggest complete removal of 10^5 CFU/100 mL after 1,5 m ground passage and risk of virus break through only with high hydraulic loading rates of 0,6 – 1,2 m/day. Considering bacteria counts of maximal 10^4 and smaller hydraulic loading rates, the unlikelihood of parasites in irrigation water and the expected adsorption capacity of high clay content in soil allows the conclusion that pathogens contamination of ground- or surface water will not occur in the Magabheni case.

For evaluation of environmental risk posed by nitrogen; leaching of the mobile form (nitrate) is the main issue. As described in the literature study, all main forms of nitrogen in wastewater can be transferred into nitrate by microbial activity of soil fauna. In Magabheni pond effluent, detected levels of the nitrogen forms: ammonia = 7 mg/L – N and Nitrate = 1,3 mg/L – N are relatively low. For retention and overall nitrogen removal of the system it is highly favourable that the main fraction of applied nitrogen is in form of ammonia (see literature study). Under given low levels of nitrogen application to the agricultural system in comparison to nutrient requirements a high crop uptake can be expected (Table 5-33). The high irrigation frequency (almost daily) practiced by farmers, retention of applied irrigation water in furrows and slightly restricted permeability of the soil might reduce aeration of the soil which results in adverse effects on the aerobic process of nitrification. Since ammonia is expected to be immobile adsorbed to the high clay content of soil, nitrification will happen eventually. In conclusion, percentile removal pathways of nitrogen from the soil presented in Table 5-21 are expected to be high for crop uptake and gaseous loss due to denitrification of microbial active agricultural soils. Nevertheless there is also a fraction of mobile nitrogen expected to leach out. Nitrogen leaching can cause eutrophication in surface water bodies and contamination of aquifers. Leaching of nitrogen or more specific of nitrate into potable aquifers (which is not the case for Magabheni, but will still be performed for to sake of a systematic approach) is critical since health risks might occur particularly for infants under 6 month consuming water with access nitrate/nitrite ("blue baby syndrome"). In comparison to German regulations on drinking water with limits of 50 mg/L nitrate (=11,3 mg/L NO_3-N) and 0,5 mg/L nitrite (Gimbel *et al.*, 2004), and U.S. guidelines of 10 mg/L NO_3-N (Crites *et al.*, 2000), South African guidelines with a thresh value of 6 mg/L for Nitrate and Nitrite together (DWAF, 1996) appear to be rather strict.

The concentration of nitrogen in total annual leaching water can be calculated with a simple mass balance based on previously made assumptions. Irrigation water has a concentration of 8,3 mg/L - N total nitrogen of which conservatively 50% is taken up by crops and 20 % is lost to the atmosphere. The remaining 30% are equal to 2,5 mg/L – N. Due to ad- and desorption and microbial transformation of ammonia the leaching rate of total nitrogen is assumed to be disconnected from the percolation rate of water, which leaves the conclusion that nitrogen is leached out slowly over the year by the total amount of water reaching the field. The total leaching reservoir of nitrogen – N supplied by 1411 m^3/ha·year irrigation water after subtraction of mentioned losses is 3,5 kg/ha. The total percolating water can be estimated by subtracting total crop water demand for assumed two planting phases of cabbage (7771 m^3/ha·year) from the total amount of water reaching the field (10281 m^3/ha·year). Calculated 2510 m^3/ha year potential percolating water carry the 3,5 kg nitrogen – N from the soil. Consequently, leaching water has a concentration of 1,4 mg/L – N which is far under the recommended 6 mg/L for drinking water.

For Phosphorus the removal in the soil is expected to be close to 100% due to high absorption capacity of the soil and high plant uptake due to a phosphorus deficit in the fertilizer balance.

Trace metals applied in irrigation with treated wastewater might accumulate temporary or over long term in the soil profile by adsorption or are in few cases extracted by crops. Trace elements which are not complexed 'infinitely' in the soil or not extracted by plants will leach out eventually into the groundwater. In a conservative approach suggested by Crites *et al.* (2000) concentration of trace metals in irrigation water can, analogous to leaching nitrogen,

be evaluated according to guidelines on drinking water. Due to absence of measurement data in Magabheni, the earlier cited study by Pettygrove and Asano (1985) on 12 municipal treatment plant effluents in California can again be used for evaluation of environmental risk (evaluated with drinking water guidelines) posed by trace elements. With Californian drinking water guidelines Pettygrove and Asano (1985:3-28) find that 5 of the 12 effluents have slightly too high concentrations for 1 – 3 metals each out of 16 sampled metals, from perspective of drinking water quality guidelines. These are chromium, copper, iron, manganese and lead. Taking the same effluents and evaluating them with South African drinking water guidelines (DWAF, 1996), which are more stringent for most elements, results in a more pessimistic picture. Particular arsenic, cadmium, mercury, lead and selenium are not conforming with South African drinking water guidelines. Applying the earlier developed relation of annually applied irrigation water to water percolating into groundwater (Ratio of approx. 0,5) results in lower concentrations of trace metals potentially reaching the aquifer. Overall consideration of the small amount of irrigation water applied in Magabheni, high adsorption potential of the soil and the absence of drinking water production from underlying aquifers suggest that trace metals are not an issue for the Magabheni irrigation project.
The concentration of salts in irrigation water has already been evaluated in Table 5-32 for the SAR value. Leached salts might increase salinity levels of the aquifer slightly but exact calculations are abolished since no direct health risks are expected to occur as described for sodium where there is only ecstatic and taste concerns in drinking water regulations of South Africa (DWAF, 1996).

Conclusion

Evaluation of potential pollution risks for the environment by the intended farming system under irrigation with Magabheni pond effluent reveals that no significant environmental contamination has to be expected. Concentrations of relevant substances in irrigation water origin from pond effluent are relatively low and the treatment capacity of the soil is large in comparison to the little volume of applied contaminated water. Filtration and activity of soil microorganisms is expected to remove all decomposable substances. Only not biodegradable substances like trace metals, salt and nitrogen are expected to be able to leach out into aquifers or surface water and pose a potential risk to the environment. Risk of leaching water into the aquifer is evaluated according to drinking water regulations. Considering the proportion of annual applied irrigation water to percolating water of 1:2, the environmental risk of leaching substances are shown to be negligible for the Magabheni case.

5.3.5 Development of contextual adapted strategies to manage risks associated with irrigation with treated wastewater in Magabheni and final project design.

In this chapter a crucial step of the design approach for agricultural irrigation with treated wastewater in Magabheni as introduced in appendix 9.5, will be discussed. By development and partial establishment of a preliminary agricultural system design based on farmer's objectives and needs, risks attached to the proposed farming system were evaluated. A risk assessment and evaluation was carried out for the three domains:

- Risks of environmental pollution;
- Risks for the agronomic system;
- Health risks.

In this design step risks origin from all three domains will be compiled in order to develop an overall strategy for risk management concluding in a final system design.

Regarding risks of the three domains it could be found that with the proposed preliminary farming system based on farmers objectives no significant risk is posed to the environment by irrigation with Magabheni pond effluent.

The evaluation of risks for the agronomic system on the basis of given effluent quality and the proposed farming system revealed that no adverse effects on agricultural productivity are expected. Only occasional high pH values in pond effluent were identified as peculiar with unknown consequences on soil-water-crop relationship. Diurnal pH variations with high pH during the day and low pH during the night were identified to be responsible for high pH values in the treatment pond system.

Assessment of microbial health risks resulted in the finding that health risk for consumers of agricultural products irrigated with Magabheni treatment pond effluent might exceed the tolerable additional disease burden of 10^{-6} DALY suggested by WHO (2006) guidelines. Health risks for farmers are also relevant but have not been investigated into depth.

Intervention measures for identified risk factors in wastewater irrigation can either be carried out by technical interventions on supplied wastewater quality, by on-farm measures carried out by irrigating farmers or post harvest food processing.

The project facilitator: Khanyisa Projects practices a community driven project design and is consequently seeking to develop risk reduction strategies in collaboration with farmers. In order to develop, discuss and decide on possible health risk reduction strategies farmers are impart a certain understanding of potential risks attached to irrigation with effluent. For this purpose a two days workshop was organized in August 2009 to educate farmers in a simple way mainly about pathogen pathways and potential on-farm intervention measures (identified by the QMRA of this document and WHO (2006)). During the workshop intense discussion amongst farmers occurred about feasibility of different health risk reduction measures which yielded in an agreement about on-farm measures to be taken.

During assistance in project planning for Khanyisa Projects the QMRA model was preliminary. The preliminary QMRA suggested less Log reduction to be necessary in order to reach the health based target of 10^{-6} DALY.

During the workshop various invited teachers referred about microbial risks for farmers and crop consumers. It was suggested to extract water only in the early morning from the treatment ponds due to water quality related to the pH. This was well accepted by the community and turned out to be anyways the case since the irrigation water storage tanks are filled in the early morning before work starts in the garden.

Measures on health risk reduction for consumers of agricultural products received a lot of attention since farmers consume a part of the planted vegetables by themselves and the implications on marketability of crops in case of disease incidences amongst customers is feared. After understanding pathways of crop contamination, the discussion yielded in the collective decision for labour investment to construct furrows with raised beds as irrigation method, allowing a die-off phase of at least 3 days before harvest by stopping irrigation and storage of harvested crops on the relatively clean concrete floor of the installed pack shed. During discussion farmers abandoned the prior favoured option of sprinkler irrigation. The option to reduce health risk by crop restrictions by abandoning plantation of crops eaten raw was not accepted, since cabbage plantation seemed to be of high value for farmers.

For personal health risk reduction, farmers understood and agreed on good hygiene praxis like washing hands after work and before eating. Furthermore, discussions yielded in a demand for a standpipe or semi pressured water tank on the field since no fresh water source for personal hygiene practice is available on site. It was also agreed to lock the farm gate after work to avoid children playing unsupervised on the field. Irrigating exclusively at the end of the day to allow infiltration of water before walking through furrows to reach the crops in the next morning and the use of closed shoes was understood as appropriate to reduce skin contact with irrigation water. Using gloves though was subject to continuous critical discussion since farmers fear that people will become suspicious about edibility of crops if they see farmers handling these with gloves.

After the workshop a final project design could be proposed. The system is very similar to the preliminary design developed purely on farmer’s interests. The final project design consist of a 1 ha fenced agricultural site with a gravity supplied irrigation system. The irrigation method is furrow irrigation with raised beds and all vegetables consumed in the area besides of root crops consumed raw could be grown. A stand pipe or drinking water tank would be supplied to the community as well as closed shoes and gloves for work in the garden.

The developed agricultural system with agreed upon on-site measures was found to be sufficient for health risk reduction to meet health based targets and to be fit to be carried sustainably by farmers after withdrawal of the project facilitator.

After remodelling the QMRA two more Log reductions of pathogens on crops were found to be required to meet health based targets. Possible options for further reduction are indicated in the following chapter.

6 Conclusion

In this chapter hypothetical wastewater management systems for the Magabheni community gardens are developed. Findings from risk assessments are used to determine case specific qualitative requirements for irrigation water resulting in possible choices of treatment technology.

Contextually developed treatment requirements are compared with national guidelines. Required effluent quality depends on crop choice, but in contrast to national guidelines also on on-farm management. Climatic conditions have been shown to be crucial for the amount of required irrigation water and consequent evolving risks.

In the case study the main objective of farmers is to produce crops for human consumption which contribute to household food security and income generation. For this reason possible wastewater management systems are analysed exclusively on basis of requirements for irrigation of food crops and not other agricultural products, which might be possibly irrigated with lower quality water.

Relevant substances in sewage water can be distinguished in chemical constituents responsible for risks posed to the environment and agronomic system, and microbial contaminants relevant for human health.

To find treatment goals for microbial constituents of raw sewage the assessment of health risks reveals the need to differentiate among the pathogen groups: bacteria, viruses, helminth and protozoa. Bacteria (e.g. faecal coliforms, *E.coli*) as indicator organisms are useful for an estimation of pathogen concentrations in raw sewage but do not reflect the effects of treatment mechanisms exact enough to design a wastewater management system for agricultural irrigation (WHO, 2006; DWA, 2008). QMRA was exclusively applied for the worst case scenario of raw consumed cabbage whereas subsurface grown root crops potentially consumed raw (Carrots) were not subject of performed risk evaluation. Required pathogen reductions to meet health based targets suggested by WHO (2006) for crop consumption patterns found in Magabheni are developed in this document for the specific bacteria (*Champylobacter*) and virus (*Rotavirus*). The assumption of Seidu et al., (2008) that *Champylobacter* and *Rotavirus* can be used as quantitative indicators for the pathogen groups; bacteria and viruses respectively is followed. This hypothesis allows the conclusion that calculated required log reduction for the two species counts also for the corresponding group of pathogens.

Required pathogen reduction for helminth and protozoa was not investigated by QMRA for the Magabheni case. In WHO (2006) and WHO (1989) helminth eggs are suggested to be reduced to maximal concentrations of 1 egg/L. Regulations stipulate, that helminth target values should be met when water is applied to the field, since WHO guidelines on helminth are mainly motivated by health risks for farm workers. In this document the focus lies on health risks for consumers of agricultural products and therefore on-farm measures to reduce helminth contamination to meet health based targets are included.

To define target values for protozoa it is recognised that WHO (2006) gives only medium importance to protozoa, due to limited evidence of disease outbreaks in contrast to high importance for bacteria, viruses and helminth. Therefore the required log unit reduction for helminths is also assumed for protozoa even though later might be present in higher numbers in raw sewage.

The found qualitative requirements are shown in Table 6-1, whereas necessary reduction of pathogens has to be achieved before consumption and can include on-farm measures. Dependent on established on-farm health risk reduction measures required effluent quality from wastewater treatment has to be adjusted. The required pathogen reduction is based on a reference irrigation method by sprinkler irrigation for raw consumed cabbage irrigated with the required irrigation water quantity for Magabheni. Necessary pathogen reduction is displayed in maximum pathogen concentrations at time of harvest inclusive associated Log-unit reduction. A differentiation of required pathogen reduction for crops consumed raw and cooked cannot be made with the developed QMRA. Even though; “cooking vegetables achieves an essentially complete reduction (5-6 Log-units) of pathogens.” (WHO, 2006: 78) Findings from the QMRA model for raw consumed cabbage cannot be transferred for crops consumed cooked since consumption patterns (dose of exposure and exposure event per year) are expected to be different for cabbage salad as side dish and a frequently consumed main dishes with cooked vegetables.

Developed treatment goals to produce desired chemical irrigation water quality for the Magabheni case can also be found in Table 6-1. Presented chemical water quality shows approximate maximum values for effluent quality. It is based on evaluation of risks for the described agronomic system with year around full plantation of the reference crop cabbage in the Magabheni community gardens under furrow irrigation.

Definition of maximum concentrations of water quality for the agronomic system is grounded on the statement by Metcalf and Eddy (2003) that mineral substances in wastewater, besides of nutrients do not modify significantly by wastewater treatment. Therefore, in the following estimation of treatment goals these are not included and the risk of salting-up during treatment is represented by electric conductivity and TDS. In Magabheni pond effluent conductivity is found to be 0,6 dS/m, this allows the assumption that raw wastewater has a electrical conductivity of < 0,6 dS/m. Target concentrations for parameters relevant for the agronomic system are chosen from the slight to moderate restriction category of Ayers and Westcot (1989). The selection respects the fact that only 14% of total annual water reaching the field comes from irrigation water and a high total leaching fraction of 2,4 could be calculated. Dilution or wastewater constituents in the soil and high leaching will avoid accumulation of toxic substances in the root zone.

Target values for parameters relevant for environmental contamination are chosen from the upper end of possible land treatment applications presented by Crites et al. (2000) since annual hydraulic loading of irrigation water is only 2 - 23% of the ones discussed in Crites et al. (2000) for slow rate land treatment systems. For organic substances Crites et al., (2000) state that land treatment with 300 mg/L BOD_5 is possible. Since BOD_5 is always smaller then COD and due to described low hydraulic loading rates it is assumed that irrigation water with COD of 300 mg/L is acceptable. For TSS the same approach is taken, on the basis of the evaluation of Crites et al., (2000) that the amount of suspended solids in typical municipal wastewater up to 350 mg/L should not be a limiting factor for land treatment. Pathogenic organisms with concentration of 10^5 CFU/100 mL faecal coliforms are degraded or filtered effectively by infiltration though the soil (Crites et al., 2000). For phosphorus a high absorption capacity of soil and uptake by crops can be assumed (Crites et al, 2000). Therefore applied concentration of maximal 12 mg/L-P in raw sewage (Metcalf and Eddy, 2003) will not be critical for environmental pollution.

Total applicable nitrogen in irrigation water can be calculated on the one hand to be 36 mg/L-N on the basis of permissible nitrate concentration of 6 mg/L-N in groundwater stipulated by South African drinking water regulations. The calculation was done according to the calculation presented above on nitrogen leaching risk. On the other hand, it has to be considered that fertilizer might be supplied to the field and leaching of the nitrogen fertilizer might become a much higher environmental contamination factor then nitrogen supplied by irrigation water. To defray the total annual fertilizer requirements of approximately 300kg/ha· irrigation water should have a nitrogen concentration of > 200 mg/L-N. Due to these conflicting interests no treatment target is fixed for total nitrogen of 70 mg/L-N expected in raw sewage (Metcalf and Eddy, 2003). However it is suggested to apply nitrogen mainly in form of ammonia or organic nitrogen since these compounds better retained and eliminated in the soil then nitrate, which reduces total nitrogen leaching to the groundwater (Crites et al, 2000, Paul and Clark, 1989).

Trace metals are not considered in established treatment targets for environmental and agronomic risks, since their occurrence is expected to be neglectable in pure domestic sewage (Lier and Huibers, 2009) as given in the Magabheni case. The absence of a productive aquifer underneath the community gardens makes management of environmental pollution risk by leaching components also insignificant.

Table 6-1: Wastewater treatment goals based on risk assessment for the case of Magabheni and assumed raw sewage water quality on basis of Metcalf and Eddy (2003).

	Assumed Raw wastewater quality (high strength) (Metcalf and Eddy, 2003)	Maximum concentrations in irrigation water / required pathogen reduction before consumption for microbial parameters
	health aspects	
faecal coliform [CFU/100mL]	10^6 - 10^8	10^0 – 10^2 (6 Log)
Enteric viruses [MPN/100mL]	10^3 - 10^4	10^{-4} – 10^{-3} (7 Log)
Helminth [MPN/100mL]	10^1 - 10^3	10^{-3} – 10^{-1} (4 Log)
Protozoa [MPN/100mL]	10^4 [a]	10^0 (4 Log)
	agronomic aspects	
Electric conductivity [dS/m]	< 0,6	3
TDS [mg/L]	860	1000
Nitrate [mg/L – N]	0	30
pH	6,5 – 8,5	6,5 – 8,4
	environmental aspects	
COD [mg/L]	800	300
TSS [mg/L]	400	350

[a](source: Pettygrove and Asano, 1985:10-8)

For the selection of appropriate treatment systems reduction of pathogens is the main treatment objective. In primary and secondary treatment processes triggering pathogen reduction, organic and suspended solid loads are usually reduced simultaneously by sedimentation, filtration or biologic degradation (DWA, 2008). Disinfection processes can only be applied effectively if preliminary removal of organic loading is performed (Metcalf and Eddy, 2003). Possible treatment processes for pathogen reduction can be found in WHO (2006) guidelines and DWA (2008) treatment recommendations. On-field measures to reduce health risk were retrieved from WHO (2006) and developed during the performed QMRA under assumptions justified above. Die-off on the field is assumed to not be an effective measure to reduce health risks from protozoa cysts and helminth eggs, since they are highly resistant to environmental conditions (WHO, 2006; Metcalf and Eddy, 2003). The difference of health risk for consumers by using furrow irrigation in comparison to sprinkler irrigation was presented to reduce risk of crop contamination for all pathogens by 1-2 Log-units. Table 6-2 presents possible measures to reduce health risks to acceptable levels to meet health based targets. The selection of measures is a matter of management approach since it includes treatment of wastewater, on-farm management measures and post harvest product processing, which is connected with crop restrictions. Reducing health risks by wastewater treatment might entail high financial and infrastructural input. Reducing health risks by crop restrictions, for example to plant only crops not eaten raw by men requires a certain acceptance amongst farmers and an enabling institutional setting. In WHO (2006) crop restrictions are presented to only be possible if “a law-abiding society and/or strong law enforcement exists; a public body controls allocation of the wastes […]; an irrigation project has strong central management; there is adequate demand for the crops allowed under crop restriction, […] and there is little market pressure in favour of excluded crops." (WHO, 2006: 76). These requirements were not entirely given for the Magabheni case which can also be seen in the detailed case study in Appendix 9.5.

On field measures to reduce health risks as recommended by WHO (2006) and the developed QMRA in this thesis require acceptance and understanding of farmers. In the case study (Detail in Appendix 9.5) it could be shown that on-field measures to reduce health risks are possible to implement by intense project facilitation and negotiation with local farmers during project planning and implementation.

Table 6-2: Measures for pathogen reduction for irrigation with wastewater [Log-unit reduction] (source: WHO, 2006; DWA, 2008).

	Bacteria	Viruses	Helminth	Protozoa
Required Log-unit reduction to meet health based targets of 10^{-6} DALY (WHO, 2006)	6	7	4	4
Wastewater treatment				
Pond treatment	5	3	3	4
Sedimentation	1	1	1	1
Activated sludge	2	2	1	1
Membrane (UF/MF)	5	4	5	5
Constructed wetland	3	2	3	2
Quick coarse sand filtration	3	3	3	3
Chlorination	5	3	1	1
Wastewater treatment and storage tank	5	3	3	3
On field measures				
Furrow irrigation	1[a]	1[a]	1[a]	1[a]
Drip irrigation	2	2	2	2
3 days pathogen die-off	1[a]	1[a]	0	0
7 days pathogen die-off	2[a]	2[a]	0	0
10 days pathogen die-off	3[a]	3[a]	0	0
Post harvest crop processing				
Peeling	2	2	2	2
Cooking	5	5	5	5
Washing	1	1	1	1

[a] assumptions and findings from QMRA case study in this study

For the case of Magabheni, farmers agreed upon using furrows as irrigation method and allowing a three days pathogen die-off on the field by stopping irrigation before harvest. With the QMRA developed pathogen Log reductions to meet health based targets of 10^{-6} DALY for cabbage consumed raw in the Magabheni case with the combination of applied wastewater treatment and on-farm measures are visualized in Figure 6-1. Viruses need to be reduced by additional two Log reductions. Further pathogen die-off or the pre-treatment by a constructed wetland is recommended as visualized in appendix 9.4. As presented in the case study, chemical parameters are reduced sufficiently by pond treatment to meet targets for environmental and agronomic risk management.

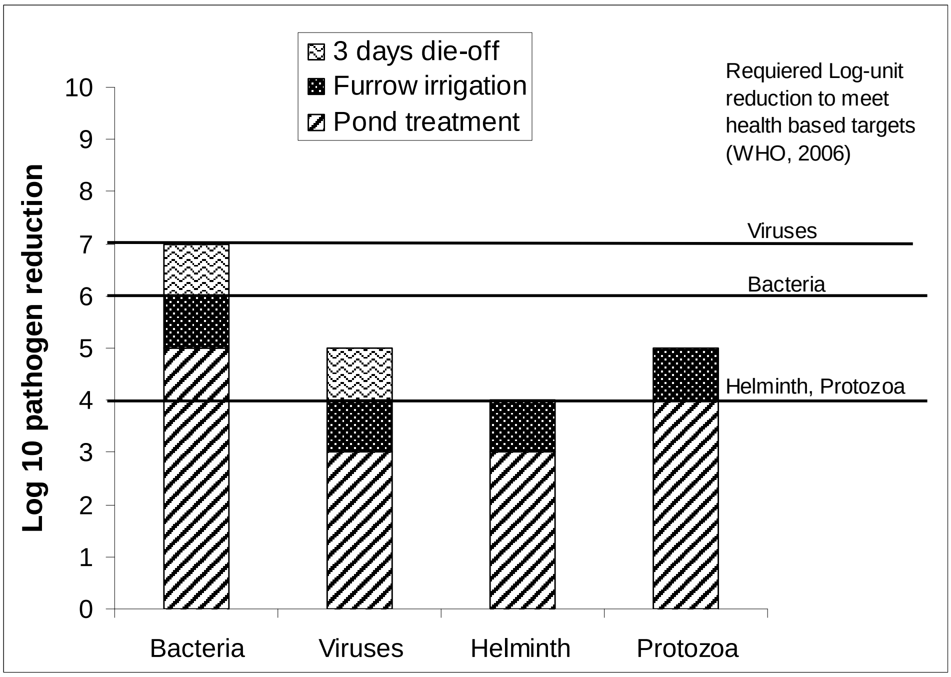

Figure 6-1: Comparison of required pathogen reduction to meet health based targets of 10^{-6} DALY and established measures for pathogen reduction for the Magabheni case.

To give two examples how health risks for consumers for the case of Magabheni community gardens could be managed with a different wastewater management system, the presented health risk reduction measures of Table 6-2 can be used.

Figure 6-2 and Figure 6-3 show hypothetic combinations of measures to meet health based targets assuming that all treatment processes are designed such that they meet treatment goals as specified in literature.

In the first example wastewater treatment is performed by sedimentation without flocculation which requires low to medium investment and operational costs with high process stability. It potentially reduces all pathogens by 90%, COD up to 35%, TSS up to 65% and ammonium and phosphorus up to 30% (DWA, 2008). Treatment by a constructed wetland may potentially remove 2 Log-units viruses, 3 Log-units bacteria, 2 Log-units protozoa and 3 Log-units helminth. Investment costs for structural engineering and surface requirements are relatively high, whereas operational costs are low. COD is removed up to 85%, suspended solids up to 90% and nutrients depending on season and age around 50% (DWA, 2008). As irrigation is applied by furrows and a 10 days die-off phase without irrigation before harvest is allowed, this hypothetical wastewater management concept appears to be sustainable in terms of management of health, environmental and agronomic risks while having low overall investment costs. Facilitation and negotiations with the farming community have to be intense and performed during the project planning phase to evaluate if a 10 days die-off is implementable or if further treatment steps have to be implemented. Possible discussion base could be price increase for irrigation water due to additional wastewater treatment steps.

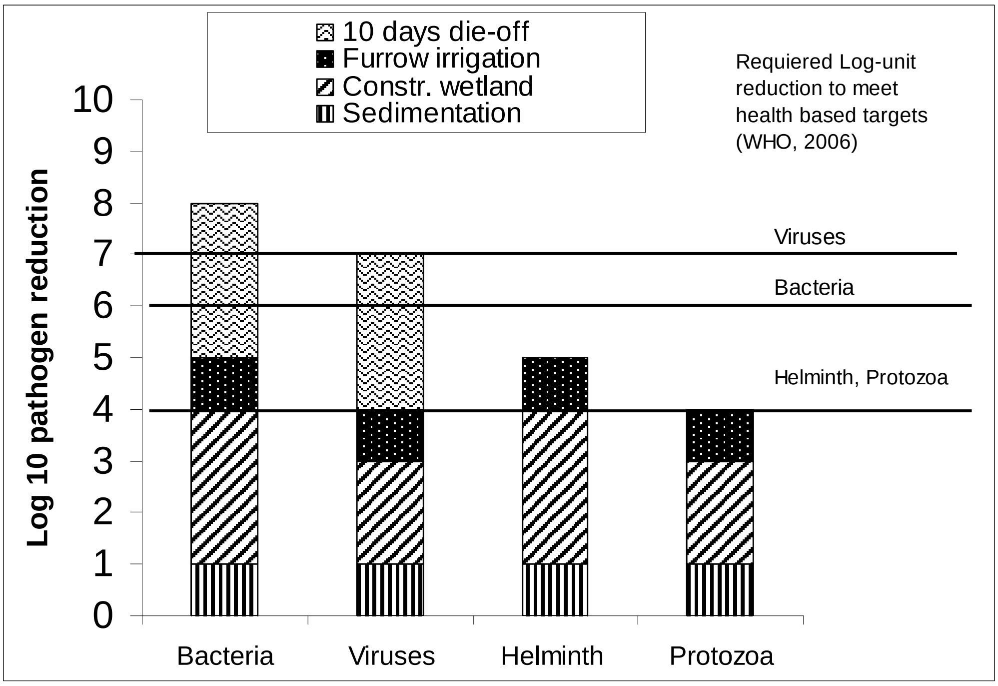

Figure 6-2: Hypothetical wastewater management scenario to meet health based targets of 10^{-6} DALY for the case of Magabheni community gardens with wastewater treatment by sedimentation a constructed wetland, furrow irrigation and allowing a 10 days pathogen die-off.

In the second scenario wastewater treatment is performed by an activated sludge process whereas a preliminary screening would be necessary to be performed (Metcalf and Eddy, 2003) which has no significant effect on pathogen concentration in wastewater. Screening without precipitation/flocculation with low investment and medium operational costs could reduce COD up to 25%, suspended solids up to 85%. Activated sludge processes without nutrient elimination, medium to high investment and operational costs, reduce COD effectively up to 90% and suspended solids up to 90%. Bacteria and Viruses can potentially be reduced up to 99% and helminth and protozoa up to 90%. Dependent of process design phosphorus might be reduced up to 30% or up to 90% (with precipitation) and ammonia will be transferred to a large extent to nitrate, which is an undesirable effect for the risk of nitrogen leaching. The two processes have a high production of biosolids which poses a disposal problem to the system. The treatment process of quick filtration with coarse sand has low investment and operational costs, with minimum COD removal rates of 20% and suspended solids minimum 50%. Nutrients have a medium removal during the process and all pathogens have removal rates up to three Log-units (DWA, 2008). With the chemically high quality effluent drip irrigation can potentially be operated which reduces health risks by all pathogens up to two Log-units (WHO, 2006). The presented scenario represents a high investment process combination, without required community facilitation but with an efficient irrigation system which would be of particular interest in water scarce scenarios.

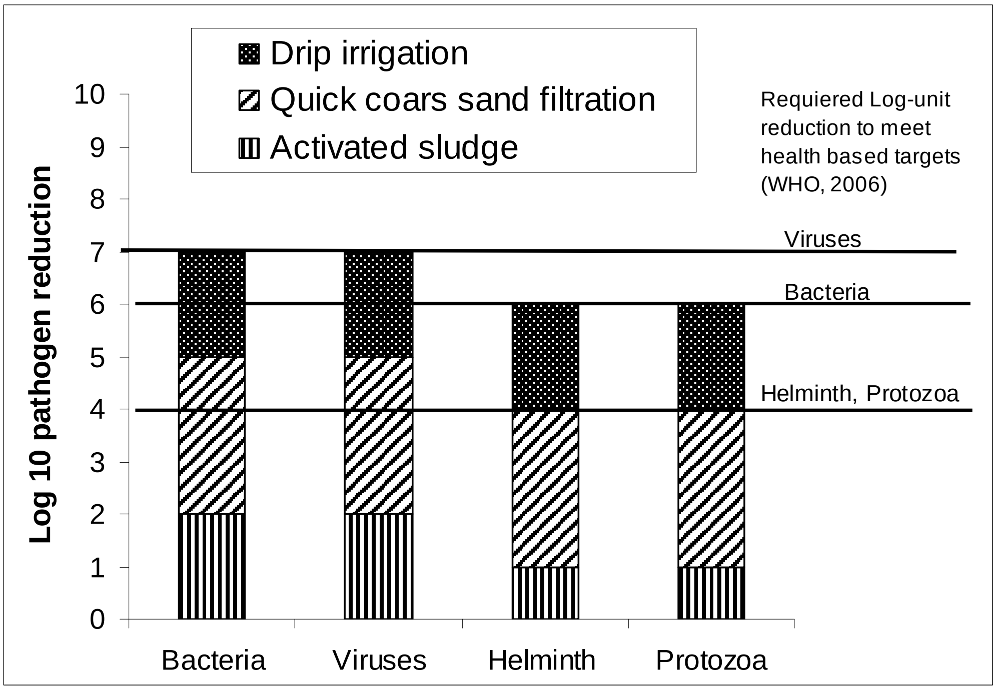

Figure 6-3: Hypothetical wastewater management scenario to meet health based targets of 10^{-6} DALY for the case of Magabheni community gardens with wastewater treatment by activated sludge treatment, quick coarse sand filtration and drip irrigation.

To compare possible designs of the wastewater management system on basis of contextual risk evaluation with wastewater management designs demanded by national guidelines, legislative documents of the Republic of South Africa are reviewed. Legislation on irrigation with treated wastewater by the South African Department of Health stipulates, depending if the crop is consumed raw or cooked, two different sets of effluent quality. Table 6-3 presents required effluent quality together with assumed sewage quality of high strength due to low per capital water consumption in rural South Africa.

Table 6-3: Treatment goals according to national regulations on irrigation with treated wastewater in South Africa and expected raw sewage quality on basis of Metcalf and Eddy (2003).

	Assumed Raw wastewater quality (high strength) (Metcalf and Eddy, 2003).	Effluent requirements for irrigation of crops not eaten raw by man (DWA, 1984; DoH, 1978).[1]	Effluent requirements for irrigation of crops eaten raw by man (DWA, 1984; DoH, 1978).
Faecal coliforms [CFU/100mL]	10^6 - 10^8	10^3 [*E.coli*/100mL]	0
pH	6,5 – 8,5	5,5 – 9,5	5,5 – 7,5
COD [mg/L]	800	75	30
TSS [mg/L]	400	90	10
Ammonia [mg/L-N]	45	1	1
Nitrate [mg/L-N]	0		1,5
Ortho phosphate [mg/L-P]	8	1	1
Residual chlorine [mg/L-Cl]	n/a	0,1	0

[1] Optional also treatment with wastewater treatment ponds with only 10^3 *E.coli*/100mL in effluent but no other specified water quality parameters.

Guidelines on wastewater treatment for agricultural irrigation of eatable crops from the Department of Health (1978) dictate possible treatment options. Wastewater treatment by a process combination of primary, secondary and tertiary treatment with the indicated effluent quality is demanded as minimum requirement. Treatment by wastewater treatment ponds is an exception and needs exclusively to comply with 10^3 *E.coli*/100mL for effluent quality. This legislative regulation allows only little flexibility for the wastewater management system to respond on needs posed by agriculture. In fact, the set effluent quality institutionalizes that planners and implementers cannot including agriculture in design of the wastewater management system to minimize costs. Only location and quantities are variable, but applied treatment technology is assumed to be chosen according to the state of the art. Effluent quality requirements for irrigation of crops consumed cooked are the same as stipulated quality for effluent that is discharged to rivers and open water bodies, besides demanding nil faecal coliforms CFU/100mL for the latter case (Durban Metro, 1997). In practice certain relations on effluent quality parameters are permitted case specific for wastewater treatment works (pers. E-mail exchange L. Moodley, EWS- Southern Coastal Area eThekwini, Jan. 2010).

For irrigation of crops which can be eaten raw by men, effluent quality guidelines are more demanding than for crops consumed cooked. Required faecal coliform count of nil CFU/100mL and high chemical effluent quality, indicates that special treatment has to be applied for irrigation which exceeds treatment efficiency of conventional treatment plants with an effluent quality comparable to drinking water quality (DoH, 1978). Regulations demand primary, secondary, tertiary treatment and an additional “advanced purification which also includes special physico-chemical purification or other advanced techniques” (DoH, 1978:3). Stipulated effluent can assumingly be used for any type of irrigation system given its high chemical and microbial water quality. Regulations are entirely focused on a crop restriction or wastewater treatment up to extreme levels allowing assumingly “zero-risk” for agricultural use. This strategy will make the wastewater treatment system and consequently the effluent very expensive. Regarding legislative requirements it can be concluded that a wastewater management system designed on context specific requirements of the agricultural setting for the case of Magabheni will be less costly than a wastewater management system for irrigation as stipulated by national legislation.

7 Discussion and Recommendations

A reverse water chain approach is a new concept of wastewater management suggesting design of wastewater management systems adapted to contextual requirements. Downstream needs and treatment potential of agriculture are considered as a starting point for integrated design of municipal wastewater collection and treatment systems. The approach intends to enable controlled, direct wastewater use in agriculture while overcoming insufficient financial, operational and institutional means for advanced wastewater treatment in low income countries.

The research at hand contributes to the contextual planning approach by elaborating water quality requirements of agriculture towards the wastewater management system.

The focus of the document lies on management of microbial health risks for consumers of agricultural products. Quantitative Microbial Risk Assessment (QMRA) is found to be a feasible tool to quantify and evaluate health risks evolving from wastewater irrigation. Health risks for consumers are evaluated on the basis of an acceptable additional disease burden suggested by WHO (2006). Allowing a certain additional health risk is a step forward to unlock benefits for health and livelihoods of farmers and the community they live in. This balanced approach overcomes the paralysed situation for wastewater management and peri-urban agriculture found in low income countries, which is created by stringent effluent guidelines based on a 'zero-risk' approach.

Exposure assessment is a key element of QMRA and identifies potential health risk reduction measures along the entire production chain, from wastewater generation till crop consumption. The assessment enables effective health risk management for wastewater use by contextual choice of health risk reduction measures. For example: In low income countries with limited financial, institutional and managerial capacity health risk reduction can be achieved with on-farm measures carried out by farmers. In high income counties choice of health risk reduction measures might be entirely on the treatment system. These examples highlight the strength and opportunities of QMRA for contextual wastewater management design in low income countries. A reverse water chain approach institutionalizes assessment of the health risk reduction capacity along the production chain and requirements of agriculture for an integrated wastewater management design.

The case study carried out in Magabheni, South Africa presents a contextual adapted exposure assessment for QMRA; uncovering the great effect farming practice and local climatic conditions have on resulting health risks for consumers. The work of the International Water Management Institute (IWMI) in Ghana shows that expanding the exposure assessment beyond the farm gate (in the research at hand exposure assessment stopped at crop harvest) reveals even more health risk reduction opportunities along the production chain (Raschid-Sally, 2009). An extended QMRA might lead to the conclusion that health risk reduction measures after crop harvest (for example during harvest storage, crop handling, transport, marketing or preparation for consumption) allow more effective and economic health risk reduction than an additional Log-unit reduction achieved by further wastewater treatment. This insight reveals that adopted management, facilitation, communication and education of and with farmers and the population has great potentials to achieve the overall goal of public health protection. Wastewater management is serving the same goal but needs to overcome disciplinary focus on pure technical measures towards integrated management including all relevant aspects to achieve a contextual sound management approach. An example of integrated management was brought forward with the case study of Magabheni, where careful facilitation with farmers during project design achieved the establishment of a wastewater irrigation system carried by farmers, reducing health risks partly by on-farm measures and creating mutual benefits for farmers and wastewater management utilities. Project facilitation and education of farmers also assured the application of personal health protection measures by farmers irrigating with treated wastewater.

Evaluation of risks for the agronomic system by wastewater irrigation was done on the basis of literature recommendations for irrigation water quality. Risks could not be quantified but maximum permissible concentrations of the most relevant chemical constituents in irrigation water were estimated. It could be shown that acceptable chemical effluent quality is highly dependent on the required quantity of irrigation water, used irrigation method and crop choice. These findings allow the conclusion that case specific design of wastewater treatment and management system for agricultural irrigation can reduce wastewater treatment costs.

In this research, environmental pollution risks are not quantified, but experiences from land treatment systems and guidelines on drinking water quality are used to estimate maximum permissible concentration of selected wastewater constituents for the Magabheni case. The estimation does not account for the large variety of environmental pollution risks and should be further elaborated with quantitative methods like Environmental Impact Assessment. Particularly trace metals and endocrine substances pose a risk for the environment which could not entirely be accounted for. Nevertheless, treatment capacity of the soil indicates effective reduction of decomposable wastewater constituents like organic substances and nutrients which is the focus of conventional wastewater treatment (Metcalf and Eddy, 2003). Also for this domain of risk, contextually adopted wastewater management by following design approaches like the reverse water chain approach are found to reveal opportunities for mutual benefits and cost savings for farmers and wastewater management utilities.

For the Magabheni case, water quality requirements indicate substantially lower treatment requirements than stipulated by national legislation. This supports the call for a shift of paradigms away from contextual unspecific guidelines towards case sensitive, integrated wastewater management.
A starting point for South Africa could be to stimulate a wide discussion on development of locally adopted health based targets as suggested by WHO (2006) which would allow local health risk evaluation. In South Africa a careful balance has to be established, respecting disease susceptibility and disease burden of the population by high HIV rates and the need for agricultural development for poverty reduction and food security.

For scientific evaluation of QMRA as a methodological approach for contextual wastewater management design current limitations due to insufficient literature data are discussed in the following. Required pathogen reduction to meet health based targets established by WHO (2006) guidelines could in this research only be based on two pathogen species. For *Rotavirus* and *Campylobacter* required data for risk characterization was available in literature. Subsequent conclusion of required pathogen reduction for the analogous groups: viruses and bacteria respectively, might not respect species specific diversity of virulence within the groups. Species specific data on disease to infection ratio, disease burden per case and susceptibility fraction required for risk characterization involves intense epidemiologic/medical research which can only be performed by experts as seen in Havelaar and Mels (2003). Enlargement of risk characterisation data in literature would enable QMRA to account for health risks evolving from a wider range of pathogens (Hamilton et al., 2005). This would increase accountability as a tool for wastewater management. As indicated in WHO (2006) an array of assumptions had to be taken for the exposure assessment due to lacking literature data on a number of on-farm processes. Remaining water on the crop as a function of irrigation system and crop morphology was almost not described in literature and had to be assumed to a large extent by the author. Movement of pathogens and interaction with root crops are beyond the scope of this research and had to be excluded from QMRA since sufficient literature data could not be found on movement and characteristics of pathogens in soil. To use the full potential of QMRA in wastewater management, additional research on mentioned aspects of exposure assessment and risk characterization have to be carried out to increase a reliable basis of scientific data.

Last but not least the applied design approach based on the reverse water chain approach is briefly evaluated. The performed study and drawn conclusions focus entirely on water quality. Development of qualitative requirements did not include perception of users based on socio-economic and cultural background of farmers. For contextual wastewater management planning these aspects are key parameters (Huibers and Raschid-Sally, 2005) and should be addressed in further research.

For integrated design as suggested by the reverse water chain approach also quantitative requirements of agriculture have to be taken into account. In the case study the small agriculture site can only use a fraction of the total occurring wastewater. In case agriculture expands or hypothetical arid climatic conditions, this situation might change. Nevertheless the fundamental problem remains that seasonal varying agricultural water demands do not match with annually relatively constant flow rates of wastewater. If a mix sewage system is in place the disposal problem for increased storm water in the rainy season, when irrigation water demand is low, even amplifies the mismatch. Potential solutions would be flexible treatment capacity to reach standards for effluent disposal in surface water bodies in the rainy season or seasonal water storage facilities which are for the case of South Africa unrealistic due to large required size for local climatic conditions.

For practical applicability of a reverse water chain approach further research should be conducted on possibilities to overcome mentioned quantitative mismatches.

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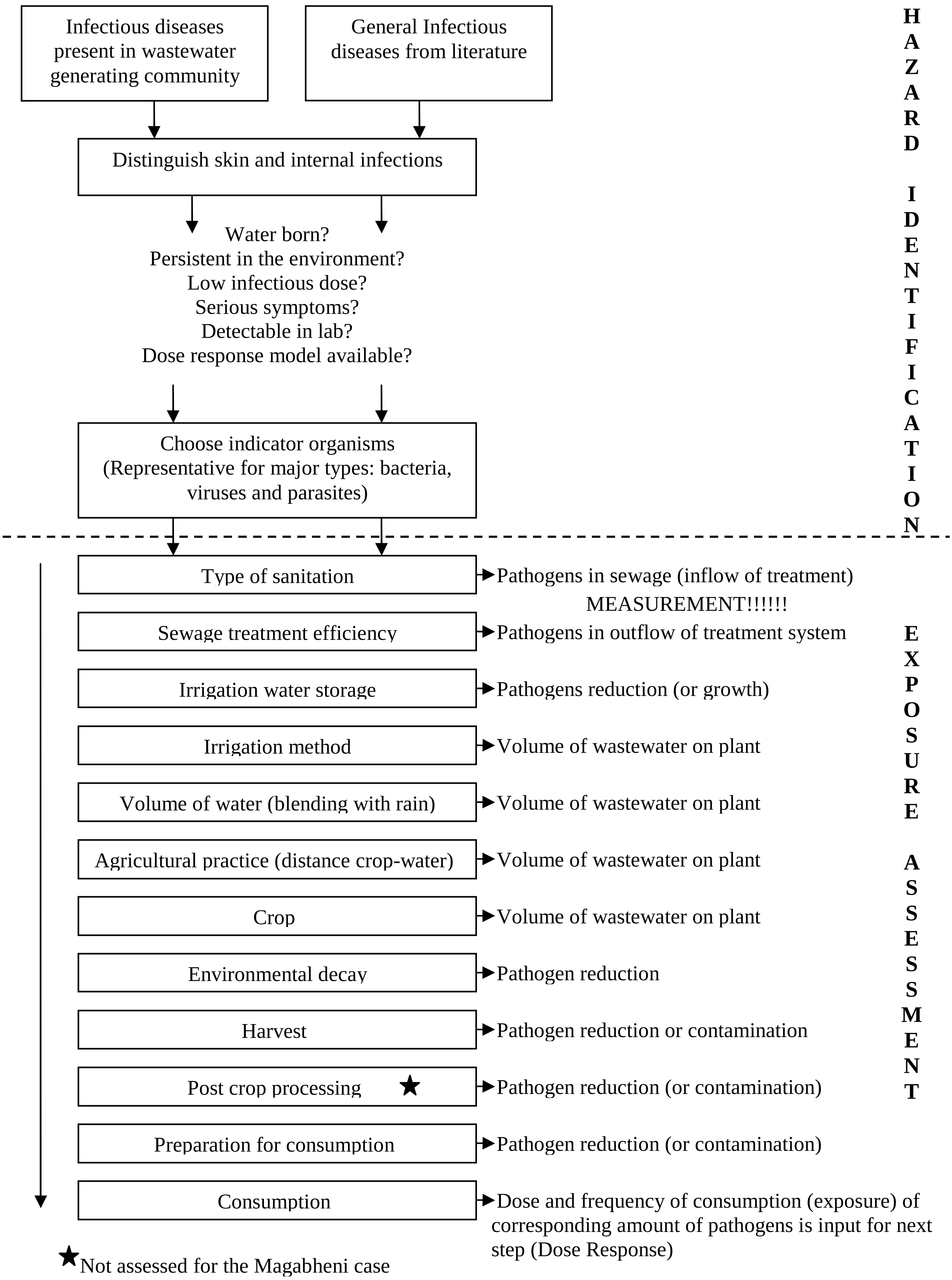
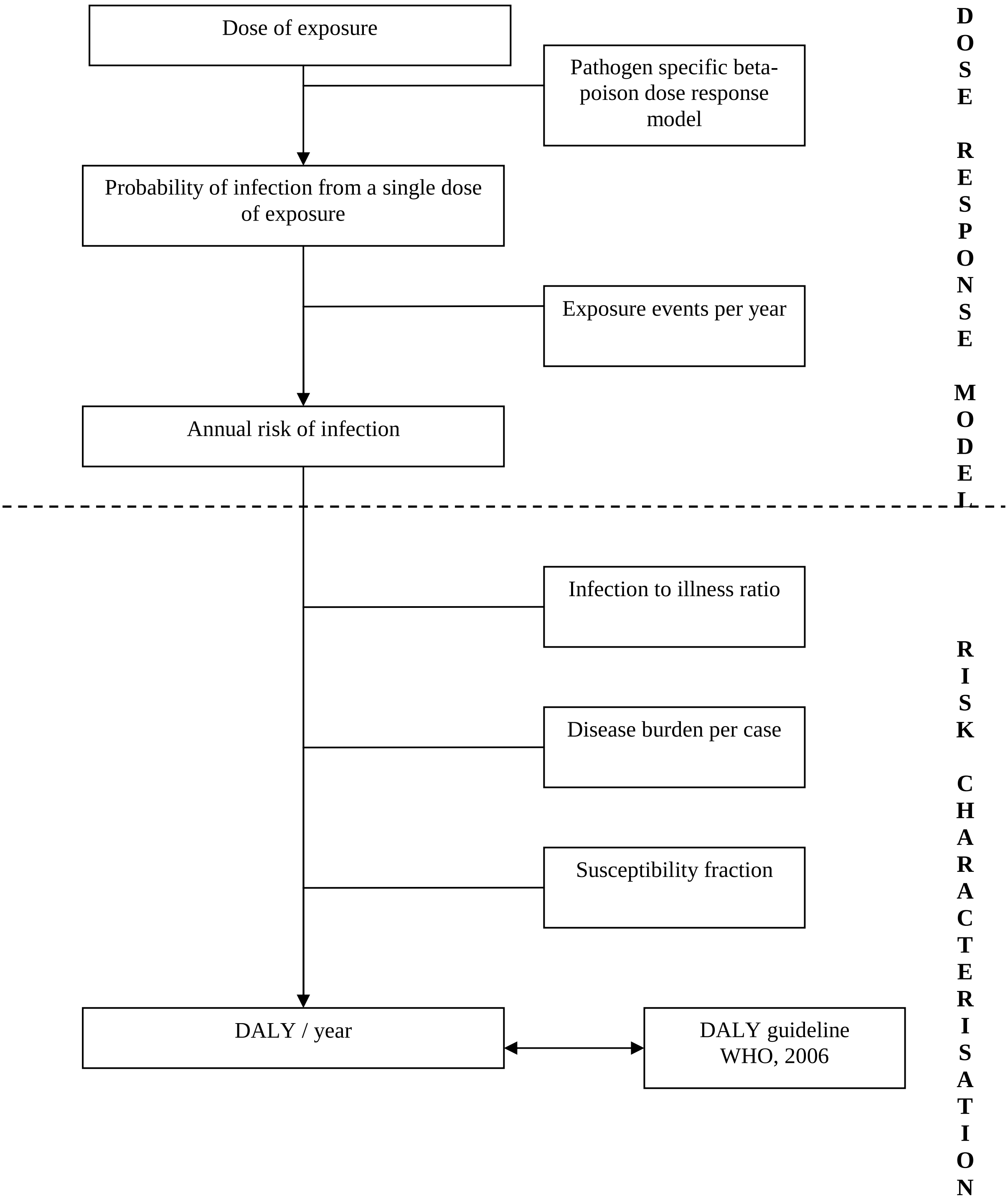
9 Appendix

9.1 Quantitative Microbial Risk Assessment scheme for Magabheni.




Dose of exposure
Pathogen specific beta-poison dose response model
Probability of infection from a single dose of exposure
Exposure events per year
Annual risk of infection
DOSE RESPONSE MODEL
Infection to illness ratio
Disease burden per case
Susceptibility fraction
DALY / year
DALY guideline WHO, 2006
RISK CHARACTERISATION

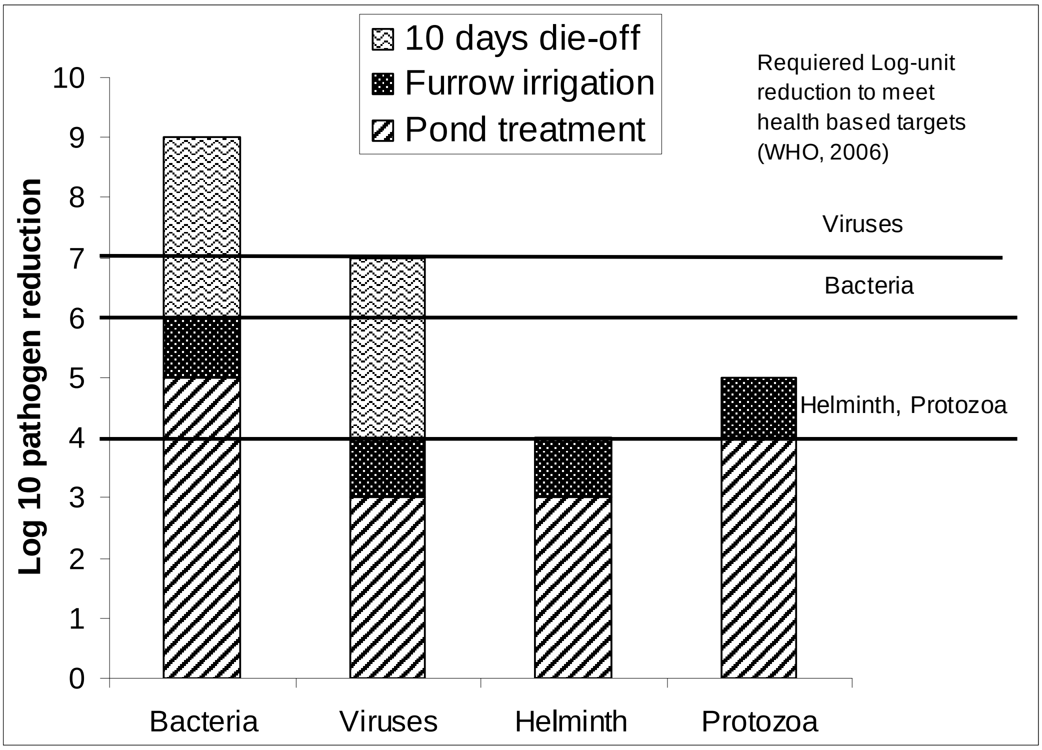
9.2 Extract of South African Water quality guidelines for irrigated agricultural use (source: DWAF, 1996b in DWAF, 2002:6-8).

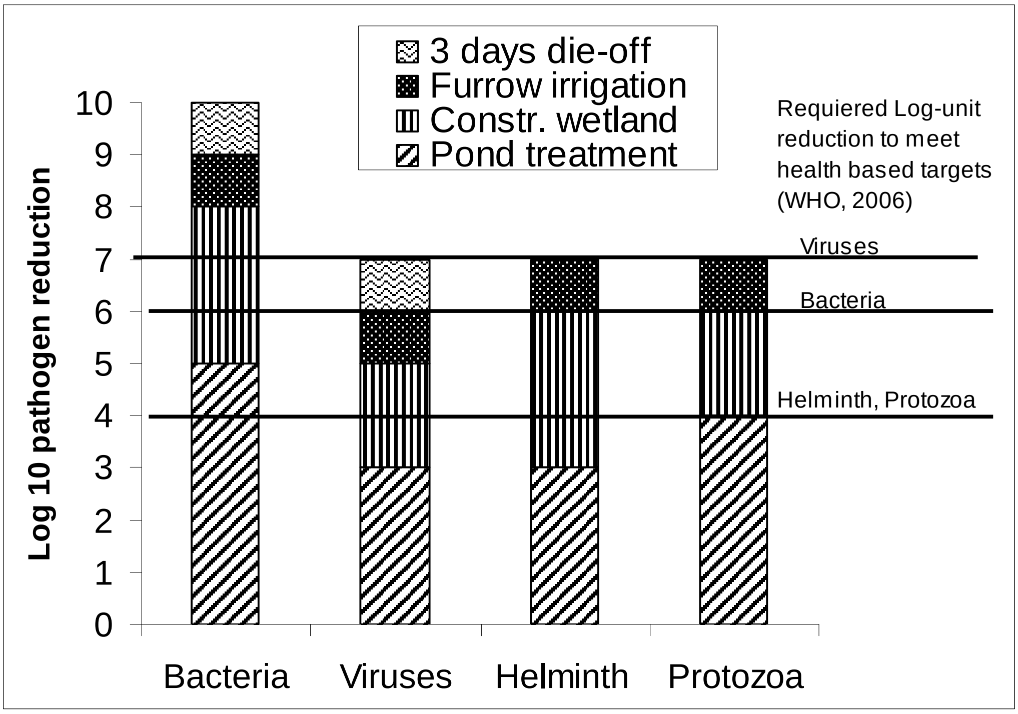
Constituent	Range	Colour Classification	Suitability for Irrigated Agriculture
SAR The Sodium Adsorption Ratio is an index of the potential of a given irrigation water to induce sodic soil conditions. Negative effects associated with soil sodicity include: reduced crop yield and quality as a result of sodium uptake through the roots of sodium sensitive plants; and impaired soil physical conditions (reduced soil permeability) (DWAF, 1996b).	≤ 2.0 TWQR	Blue **Very good water quality**	Should prevent sodium toxicity from developing, provided that water is applied to the soil surface, limiting sodium uptake through the roots.
	2.0 – 8.0	Green **Good water quality**	The most sodium-sensitive crops absorb toxic levels of sodium through roots. Crops vary in sensitivity.
	8.0 – 15.0	Yellow **Fair water quality**	Sodium-sensitive crops absorb toxic levels of sodium through roots. Crops vary in sensitivity.
	> 15.0	Red **Poor water quality**	All sodium-sensitive crops absorb toxic levels of sodium through root uptake. A number of economically important crops can be irrigated without sodium toxicity developing.
EC ($mS.m^{-1}$) Electrical Conductivity is increased when increasing levels of salt are present in the irrigation water, which introduces salt into the soil profile. When little or no leaching of the salt takes place from the soil profile, salt accumulates and saline soil is formed (DWAF, 1996b). Yield is reduced in crops that are sensitive to soil salinity.	≤ 40 TWQR	Blue **Very good water quality**	Should ensure that salt-sensitive crops can be grown without yield decreases when using low frequency irrigation systems.
	40 – 90	Green **Good water quality**	A 95% relative yield of moderately salt-sensitive crops can be maintained by using a low frequency irrigation system.
	90 – 270	Yellow **Fair water quality**	A 90 % relative yield of moderately salt-tolerant crops can be maintained by using a low frequency irrigation system.
	270 – 540	Red **Poor water quality**	An 80 % relative yield of moderately salt-tolerant crops can be maintained by using a low frequency irrigation system.
	> 540	Purple **Not acceptable water quality**	These waters can still be used for irrigation of selected crops provided sound irrigation management is practised and yield decreases are acceptable.
pH The pH value of water does not have direct consequences except at the extremes (DWAF, 1996b). The adverse effects of pH result from the solubilisation of toxic heavy metals and the protonation or deprotonation of other ions.	< 6.5	Red **Not Very good water quality (acid)**	Increasing problems with foliar damage.
	6.5 – 8.4 TWQR	Blue **Very good water quality**	Should not cause foliar damage
	> 8.4	Purple **Not Very good water quality (alkali)**	Increasing problems with foliar damage
Cl ($mg.\ell^{-1}$) Chloride is an essential plant micronutrient and is relatively non-toxic to most crops (DWAF, 1996b). However, when the accumulated chloride concentration in leaves exceeds the crop's tolerance, injury symptoms develop in the form of leaf burn that affect crop production (DWAF, 1996b).	< 100 TWQR	Blue **Very good water quality**	Should prevent accumulation of chloride to toxic levels in all but the most sensitive plants.
	100 – 175	Green **Good water quality**	Crops sensitive to foliar absorption accumulate toxic levels of chloride when foliage is wetted.
	175 – 350	Yellow **Fair water quality**	Crops moderately sensitive to foliar absorption accumulate toxic levels of chloride when foliage is wetted.
	350 – 700	Red **Poor water quality**	Crops moderately sensitive to foliar absorption increasingly accumulate toxic levels of chloride when foliage is wetted.
	> 700	Purple **Not acceptable water quality**	Crops tolerant to foliar absorption increasingly accumulate toxic levels of chloride when foliage is wetted.
B ($mg.\ell^{-1}$) Boron is an essential plant nutrient that is toxic to plant growth at low concentrations (DWAF, 1996b). Boron tends to be found in association with saline conditions.	< 0.5 TWQR	Blue **Very good water quality**	Should prevent accumulation of boron to toxic levels (through root uptake) in all but the most sensitive plants.
	0.5 – 1.0	Green **Good water quality**	Crops very sensitive to boron accumulate toxic levels (through root uptake). Plants start to display symptoms of foliar injury and/or yield decreases.
	1.0 – 2.0	Yellow **Fair water quality**	Crops sensitive to boron accumulate toxic levels and start to display foliar injury and/or yield decreases.
	2.0 – 4.0	Red **Poor water quality**	Crops moderately sensitive to boron accumulate toxic levels and start to display foliar injury and/or yield decreases.
	> 4.0	Purple **Not acceptable water quality**	Crops moderately tolerant to boron accumulate toxic levels and start to display foliar injury and/or yield decreases.

9.3 QMRA – MC Unrestricted irrigation 2 Interface from Microsoft excel based QMRA model provided by Leeds University.

UNRESTRICTED IRRIGATION: Lettuce ingestion					
Quantitative Microbiological Risk Analysis Monte Carlo simulation (**Andrew Hamilton method**)					
	Enter Values in the yellow boxes				
Variable	Range				
Faecal coliform count per 100 ml	10	1000			
No.of pathogens per 100,000 FC	100	1000			
Water on 100 g lettuce (ml)	7,78134	7,78134			
Quantity of lettuce consumed (g/day)	30	50			
Reduction factor (n log)	0	0	Factor	1	1
Exposure (every n days)	2	4	Exposure (days/year)	182,5	91,25
Disease/infection ratio	1	20			
Pathogen coefficients					
Variation from default value (+/-%)	25		◉ Rotavirus	Default values:	
N_50	4,6275	7,7125	○ Salmonella	N_50	6,17
Alpha	0,18975	0,31625	○ Shigella	Alpha	0,253
			○ Campylobacter		
Mid Percentile	50,0%		○ Vibrio cholerae		
Upper Percentile	95,0%				
Number of simulations	1000		Do Monte Carlo Simulation		
	RESULTS				
	PI Annual				
50% value =	0,99688674				
95% value =	0,99977075				
Minimum =	0,97489679				
Maximum =	0,99994511				

9.4 Visualisation of possible measures to meet health based targets of 10^{-6} DALY for cabbage consumed raw for the case of Magabheni community gardens.





9.5 Detailed description of Magabheni irrigation project history and development of proposed farming system.

Two projects for irrigation with treated wastewater are presented in the detailed case study. Both projects are located at Magabheni in eThekwini and intended to use effluent of the Magabheni wastewater treatment ponds, serving the Magabheni Township, for agricultural irrigation. Both projects were carried out for the same area. The first design was larger in size and farmers and stopped in the year 2007. The second approach was carried out as a revitalization of the old project on a smaller area and with fewer farmers. The project designs were made and shaped on basis of different starting objectives. The manifestation of the followed design approaches in the physical and managerial appearance of the agricultural project will be presented in the following.

In Chapter 5 presented physical background including wastewater collection and treatment system and climatologically conditions are for both projects identical. The case study of the old (disposal driven project design) irrigation project was not discussed in the research before. The study is based on a literature review of project documentation and interviews with project donor and facilitator and reveals design approach and outcome of the irrigation project. Afterwards the second design approach (community driven project design) will be introduced. This study comprises fundamental steps of the design approach which will be presented in detail. The second design approach is the basis for the case study discussed in Chapter 5.3.

9.5.1 Disposal driven project design

Irrigation with treated wastewater with the agricultural system in place in 2007 is the end product of various activities of different actors assigned from the eThekwini municipality. The main milestones of the project design are presented in the following.

9.5.1.1 Project design

The first initiative towards agricultural irrigation with Magabheni treatment pond effluent was made by Mr. Breetzke from eThekwini municipality *Corporate Policy Unit Department* who was from 2001 till 2007 manager of the project. During a helicopter flight in 2000 for a costal development project over the south coast of eThekwini, he noticed that the estuary of the *Ngane* river showed heavy eutrophication. Flying the *Ngane* river upstream could identify the Magabheni pond treatment system as main pollution source of the river. The idea was developed to resolve the environmental problem of water pollution by linking it to livelihood improvement of the poor local population though application of an innovative treatment process. The objective was to implement a constructed wetland for post treatment of pond effluent. The wetland was suppose to be managed by the local community and produce reed for local traditional handcraft (pers. comm.. K. Breetzke, eThekwini municipality, Aug. 2009).

To implement the project objectives, the *Institute of Natural Resources* (INR) with a track record in community development projects in the area was assigned as project implementer and delivered in October 2001 the first succinct project proposal for Magabheni. The proposal was established in the larger context of the *South Coast Cultural Ecotourism Project* which intended to promote agriculture, local crafts, culture and ecotourism in the costal area of eThekwini. For Magabheni a constructed wetland as post-treatment of Magabheni pond effluent was proposed to purify river water in order to enhance economic and touristic activity downstream of the *Ngane* river. Jobs were intended to be created for 17 members of the poor local community to construct and maintain the wetland and produce the wetland reed species *Incema* which could be sold and/or used by surrounding communities in the production of traditional crafts. The proposed two year project was label as poverty relief project. The proposal was approved by Mr. Breetzke as representative of the project owner: eThekwini (Durban Metro) and Mr S. Pillay as project donor: *Tourism Development, of Department of Environmental Affairs and Tourism of South Africa* (Enzangakho CC, 2001; DEAT, 2001).

Initial discussions with the local community showed that they did not support the project proposal of a wetland for reed production since income generation appeared to be too low. They ask for potential higher income generation and food production to give an initiative for project support (pers. comm. project managers from INR, Aug. 2009). Community desires where respected by INR and eThekwini and the project shifted to an effluent irrigation project of which a business plan and proposal was presented and the budged of approximately 110 000 € approved in January 2003. In the proposal INR suggests with *Mottram and Associates cc* as contracted irrigation specialists for irrigation system design and implementation, to split the project in two phases. Phase 1 includes the investigations and applications for required permits and the engagement of local community members to determine appropriate crops that could be grown as part of the project. The second phase would comprise the realization of the project. Further in the proposal is written that due to a conducted soil survey a 13 ha site was identified to be suitable for disposal of the entire effluent from the Magabheni wastewater treatment ponds. For this area "suitable crops would be selected though a collaborative process with the beneficiary community. It is likely that crops would include a combination of vegetables, medicinal plants and fibre producing plants. The final crop selection would be based on community needs and market demand for the various crop types." (INR, 2003A:3,4) Later in the proposal possible profit margins for planting combinations of specific fibre- and medical plant crops, sugarcane and *vegetable mix* are presented for the proposed 13 ha site under irrigation.

For the structure of the farming community it is assumed that a form of cooperative or business enterprise for joint management of the agricultural area and irrigation system may be formed (INR, 2003A).

Review of a report prepared by *Mottam and Associates cc* in February 2002 for *Magabheni Treatment Works – Water Re-use Project* reveals that the information on irrigation system design and preliminary crop selection in the INR (2003A) proposal where copied from this report. The report is proposing a disposal driven irrigation system with the notion of "top down" design, but was composed to provide information for the local community to "make an informed decision about the viability of a fertilised irrigation project and which crops should be grown on the proposed area." (Mottram, 2002:1) In the document an evaluation of analysed effluent quality on basis of quality recommendations and guidelines given for irrigation by the Government notice No 1191 of 8 October 1999 from the Department of Water Affairs and Forestry (DWAF, 1999) is carried out and effluent is found to be feasible for use. The later document authorises irrigation of maximal 500m³/d with domestic wastewater. Based on a soil study a site selection of 13 ha is proposed which allows disposal of pond effluent on preselected crops. "This 13 ha will cope with a final effluent production of 500m³/d."(Mottram, 2002:4) The assumption of 500 m³/d occurring effluent is the result of a focus on legislative guidelines while negligence of site conditions and can not be confirmed in this study with expected 200m³/d (as justified in subchapter 5.1.2). The limited crop selection (mainly medical plants and chillies as only vegetable) is justified by experiences of *Mottram and Associates cc* in large scale centrally managed irrigation projects and interviews with pharmaceutical companies as possible customer of crops. Calculation of irrigable area with 500 m³/d inflow is based on this crop selection. Organisational structure of farmers is proposed to be hierarchically ordered with a "small management team of 3 persons and an initial labour force of 20 persons to be selected by the community." (Mottram, 2002:9) The corresponding design of the irrigation system for 13 ha is a centrally (by management team) operated overhead sprinkler system with few possibilities of interaction for farmers on the field "thereof whilst not allowing it to be inefficient in disposing of the effluent in the correct manner." (Mottram, 2002:9)

A revised and detailed business plan for the project prepared by INR in June 2003 adjusted crop choice to the wish of identified 30 beneficials to mainly produce food crops with expected 40% own consumption and 60% income generation by selling of products. In the document is stated that crop choice of banana and mango trees (6 ha), chillies and pumpkin vegetables (1 ha) and Sugarcane (6 ha) was made according to desires of beneficiaries, environmental feasibility and the Department of Health (DoH) guideline for permissible utilisation and disposal of treated sewage effluent (DoH 1978) to plant crops which can be peeled (e.g. banana), processed (e.g. chillies) and/or do not fruit underground (pumpkin).

These criteria cannot be confirmed by review of the guideline (subchapter 5.2.3) and the process of crop selection remains unknown to the author.

The planned size of the irrigated site remains 13 ha. The proposed effluent disposal system is supposed to be a combination of sprinkler and micro - irrigation for fruit trees (DoH 1978). “The effluent disposal system has been designed to accommodate the rainfall and evaporation rates in the area, and the volume of treated effluent generated. The system will utilize a maximum of 500m³/d of treated effluent, depending on the rainfall. As the system is primarily for the purpose of effluent disposal, it will be a supplementary irrigation system.” (INR, 2003:7) The irrigation system remains to be central controlled to “achieve the participants’ aims and the stakeholders’ objectives” (INR, 2003:24), which means to dispose the maximum amount of effluent. In times of low irrigation water demand, water is intended to be pumped into a constructed wetland with the approximate capacity of 200 m²/d which purifies effluent before drainage into the river and produces reed plants (INR, 2003).

The first project implementation step was to apply for required legal permits. This process was delaying the process unexpectedly long since the amount of required documents was not estimated correctly during project planning.

Various institutional queries and the slow processing of applications delayed the possibility for first irrigation from end 2004 till end 2006. Due to this delay duration of project facilitation with the community had to be extended, equipment was stolen, internal conflicts within the community arose, banana trees were lost since project was not far enough progressed. At the end of 2006 the project budget was depleted, an eThekwini internal trial against two responsible project manager was held for misappropriation and not a single irrigation turn was performed with the installed irrigation system for 11 ha (Breetzke, 2007). The project did not receive further funding and project managers and facilitators withdrew in 2007 from the project leaving an operational system with all necessary legislative permissions and one butternut harvest.

In 2008 nothing more than the pump at the treatment ponds, underground piping system and the not operated constructed wetland was left on site. After harvest of and selling of the grown butternuts, farmers abandoned the agricultural project.

Khanyisa Projects, the facilitator of the continuing project states in a project report reasons for project failure from investigated point of view of the community:

“A feeling on the part of community members, is that key factor behind the stalling of the project was a lack of community participation, particularly during conceptualization.” (Khanyisa Projects, 2008b:1). Other reasons were the complex operation procedures of the highly technical and central operated irrigation system, which is seen as difficult to operate and not feasible for the community. Some valves of the large pipe ring of the irrigation system were placed without prior consultancy in gardens of dwellers that did not want to participate in the project which lead to land queries. Land queries where mixed with tribal issues and lead to social conflict within the community (Khanyisa Projects, 2008b; Khanyisa Projects, 2008c). Household interviews revealed that after selling of the pumpkin harvest social tension within the cooperative was enhanced since money from the butternut sale disappeared or was not evenly shared amongst farmers.

9.5.1.2 Conclusion

By reviewing historical project proposals for the Magabheni site and interviews with the former project manager and facilitators, it could be shown that the project design process was highly disposal driven. Initiation of the project was motivated by an environmental pollution problem of the *Ngane* river which receives Magabheni pond effluent. A strategy was developed to create mutual benefits for environment and local people who where considered to take over the project after external initiation. Linking the disposal problem with opportunities of local poor to improve their livelihoods by effluent irrigation secured also funding for the project though poverty relief funds. The irrigation system design was not in line with the project approach to develop a local agricultural project using wastewater. Physical and institutional manifestation of the irrigation system design suggests that design and planning was mainly disposal driven. Centralized operation of the whole system with no opportunity for spatial independent irrigation management by community farmers, intends to assure that potentially occurring 500 m^3/d effluent is fully disposed on 13 ha agricultural site. Design volume flow was copied from environmental regulations on maximal applicable volumes and overestimated the available amount of pond effluent dramatically.

After withdrawal of project facilitators from the established irrigation site, the local community did not carry on with the agricultural project and pond effluent was again disposed in the river. It is assumed that the site was too large and the irrigation system too sensitive and difficult to operate. The installed constructed wetland for effluent treatment is not in use since pumping is required for operation.

The project design did not put any considerations into health risk of farmers. Health risk for consumers of agricultural crops where partly regulated by crop and irrigation method restrictions by the Department of Health and regulations on maximal faecal coliform concentration in used irrigation water (DWAF, 1999). In terms of clogging and scaling of irrigation equipment and health risks for farmers by overhead sprinkler irrigation, the long term sustainability of the project design is questionable.

9.5.2 Community driven project design

In the beginning of 2008 Khanyisa Projects (consultancy) was approached by the Department of Economic Development to facilitate the revitalization of the Magabheni Agricultural Wastewater Re-use Project. In their project proposal from March 2008 Khanyisa Projects clearly state their understanding of objectives and working philosophy: “Objective of this initiative is as follows: assist the co-operative to use the land and other resources to begin to operate as a sustainable, commercial agricultural venture.” (Khanyisa Projects, 2008a:1) As critical key success factors for project progress they state that activities must be driven by the community and specifically the co-operative member. “If the municipality and Khanyisa make the decisions and take action, the project will ‘limp’ along and stop once again.” (Khanyisa Projects, 2008a:2) Khanyisa Projects aims for a two phase involvement in the project. In the first phase interaction with the community, the co-operative and key local structures are planned. The assessment of capacity and commitment of the cooperative, leadership structures, land issues, but also the inventory of existing irrigation infrastructure intends to create a basis for communication with farmers and an in-depth understanding of local conditions. The cooperative should decide freely which crops they want to plant. Khanyisa Projects recommends to start out with a small project area (2-4 ha) to give farmers the opportunity to make experiences on independently irrigated, controllable scale, to expand the irrigated area by themselves with potentially more capital, experience and cooperative member (Khanyisa Projects, 2008a).

In December 2008 Khanyisa Projects communicates some findings from the assessment phase in a project report to the project donors. During participation in a number of meetings and workshops with the community structures and garden groups they find that a fraction of the old cooperative members are motivated to re-launch the agricultural project. The interested group intends to work on a small (1,5 ha) plot of land with a simple irrigation system. Since they have no funds available they need support for revitalization and modification of a part of the irrigation system, fencing to secure land from new housing development in the area, seeds to start planting and fertilizer or compost. For the following steps Khanyisa Projects intends to use a “construction management – community responsibility” approach to ensure ownership of the project by the community and encourage “learning by doing”. The community will have to take responsibility for the materials and tasks to be undertaken, but will be supervised and supported by Khanyisa technical personal (Khanyisa Projects, 2008b).

In May 2009 Khanyisa Projects held a progress meeting about the Magabheni Farm project. Laboratory scientists from eThekwini Water and Sanitation presented results of five measurements from January till May 2009 of the Magabheni pond effluent. The results for *E.Coli* measurements from the pond outfall were initiation of an emotional discussion amongst attendant planners and decision makers. Three measurements found no *E. coli*; one detected 100 and one 1300 CFU/100 mL. These quantitative microbial data caused insecurity amongst decision makers since implications for health risks for farmers and consumers of planted crops was unclear. The agreement was made to proceed with the irrigation project implementation but to conduct further research on potential health risks evolving from irrigation with Magabheni pond effluent and how they could be managed. It was stated that either on farm practice, crop restrictions or additional treatment could minimize health risks, though a decision was left open due to missing quantitative understanding of health risks. An attendant representative of the Agricultural Management Unit (eThekwini) stated that “we need to balance the urgent need for food security and livelihoods with the risks associated with the municipality providing water with high levels of *E.coli*.” (Khanyisa Projects, 2009a:1) In the next meeting one month later, a brief research proposal (Appendix 9.6) to assist project design by conducting a household livelihood assessment on farmers and community members, assessing farmers objectives and analysing health risks by the intended farming system; was brought forward from the author and another researcher and accepted by project donors and facilitators. The study at hand comprises partly findings of the mentioned research.

9.5.2.1 Followed design approach

Khanyisa Projects intends to assist the cooperative in developing and operating a community driven irrigation project with treated wastewater. To achieve an agricultural design supported and carried by farmers the community of Beneficial’s are involved in all steps of system design. The followed design approach can be split in three steps.

The first step results in a preliminary agricultural system design based mainly on requirements and desires of farmers investigated by conducting household livelihood analysis and interviews with farmers. Specific characteristics of effluent as source for irrigation water are initially not considered. This preliminary system design is presented in the following and is the basis for earlier performed risk assessment. The system is designed, based on an iterative process. Initiatives given by assessment and interaction with the agricultural community are applied directly in praxis. Basic features like fencing and some seeds are given to farmers on basis of initial objectives to enable them to collect first experiences and sharpen the understanding of a desired preliminary design. This approach enables farmers to pose concerns and wishes for modification of the system at an early stage of design. Till that point no special considerations are given to the fact that effluent from the Magabheni pond wastewater treatment system is used as source for irrigation water.

The second step of project design comprises an evaluation of potential risks posed by the intended farming system of the preliminary design under irrigation with treated wastewater as presented in chapter 5.3. Evaluation of risks has a focus on health risks for consumers of agricultural products by microbial contamination. Additionally risks for the agronomic system and environmental contamination by irrigation water constituents are considered.

The third step in overall project design comprises the identification of locally adapted intervention measures in interaction with farmers towards potential risks as presented in chapter 5.3.5.

9.5.2.2 Community household assets and objectives of cooperative

In the following chapter relevant findings of the conducted household livelihood assessment in 20 rural households around potential agricultural site and investigated objectives of the cooperative are presented briefly.

Local community

All twenty visited households are exclusively composed of Zulu speaking black South African citizens. The average household size was nine persons composed of five adults and four children. In more than half of the households nobody is employed and investigated unemployment rate of the 20 households was 96 % amongst adults. Households sustained themselves mainly from old age grants (65€/month) of the few old people or from grants for young children (15€/month) (Makino, 2004). Households usually owned not more then the house they live in, basic furniture, cooking and some gardening (hatchet) equipment. Assumingly a lot of women were single head of family. In all households in average once a week a member goes to buy goods at the next bigger town which costs approximately 2 hours time 1,5 € for transportation.

Few households showed interest in the community garden since 18 households had their own vegetable garden in summer (Figure 9-1). The motivation to work in agriculture was in general low, particular amongst young community members. Four households keep few free grazing livestock.

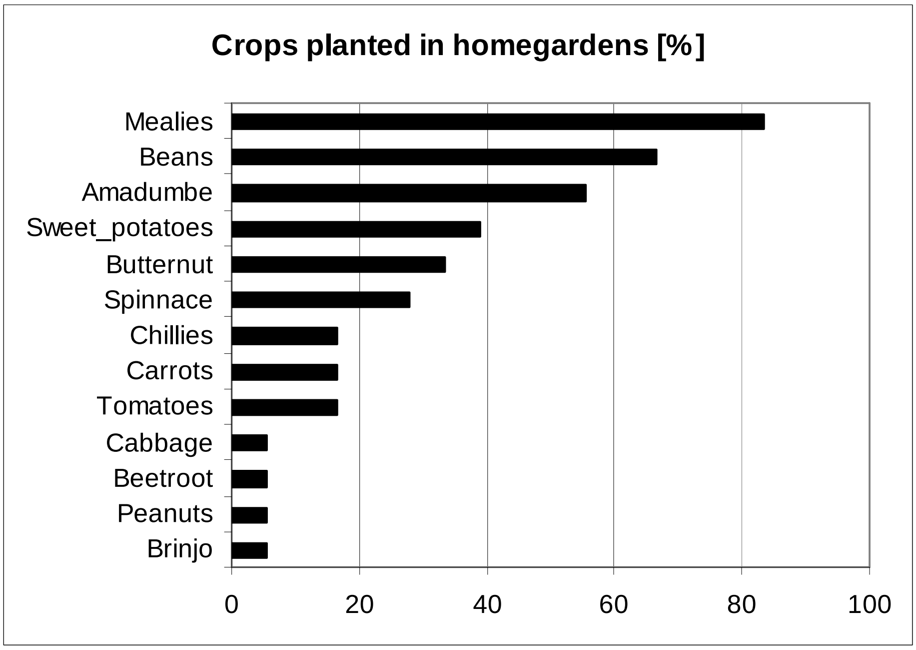


Figure 9-1: Crops planted in summer homestead gardens of 18 households close to irrigation site, investigated by household livelihood interviews.

<u>Cooperative</u>

The cooperative of the Magabheni community gardens, registered in February 2004 formally as *sisizana-zonke primary trading co-operative limited,* with about 15 members, does not exist in this form anymore. Active community members referred to as cooperative members are at present a group of informally organized local people that call themselves cooperative, however not formally registered. In this document the term cooperative is used for this informally organised group of farmers.

The cooperative is composed of five Zulu speaking black South African woman. Four of them are approximately 50 years old or older, unemployed mothers of families in the local community. One is approximately 30 years old and is occasionally employed outside of the community.

The cooperative owns a large amount of micro- and overhead sprinklers from the former (disposal driven) project. There is no experience in irrigated agriculture. Agricultural skills are learned mainly from activities in home gardens and for one case from past day labour at sugarcane plantations. Wheat and bug control has always been done by hand since there is no financial capacity to buy chemical agents. The cooperative members received a one week basic training on land management and agricultural practices and book keeping for cooperatives by Cedara Agricultural College. Other group members attended a course in banana plantation (Khanyisa Projects, 2008c).

Land rights for households and communal land are partly held by local families. Land rights in rural areas of KwaZulu-Natal are subject to legal pluralism of traditional local leaders and national government (Simpungwe, 2006). For the potential agricultural site at least two

individual community members own tenure rights which were awarded to them on request by the local *iNkosy* (traditional leader) in 2003. The farming cooperative as an entity did not lease rights and relies on informal authorization of entitled individuals to perform agriculture on the land (INR, 2003).
The social network of the cooperative within the community seems to be not very strong due to past tensions amongst the community about various topics. Nevertheless for marketing of potentially produced crops by the cooperative 19 households stated they would be willing to buy any kind of crops from the cooperative in the dry season.

Objectives of the cooperative

An agricultural site of approximately 1,5 ha in the community was identified by cooperative members to be feasible for agriculture.
All five cooperative members declare to be willing to work 6 days a week for 6 hours per day. Approximately ten children (6-14 years old) of cooperative members are meant to help during work in the field, particular during school holidays since homes are close by and they will come to visit and play on the field.
For crop choice, cooperative members state to be open to plant any type of crop. They declare to take what is supplied in form of seeds, but do want to plant crops which are marketable; whereas cabbage is often mentioned to be easy and popular to market. Since experiences with agriculture are mainly based on the crops that are planted in the homestead gardens it is assumed that these will be the most successful to plant. Since crop marketing is intended to be performed also in the local community crops grown in summer home gardens (Figure 9-1) are assumed to be well accepted. Interviewing all twenty households about their vegetable consumption habits yielded to Figure 9-2. The survey was performed by a questionnaire with common vegetables (without Peanuts) planted and consumed in the area. It was also asked if they cook the vegetables or eat them raw, double selection was possible.

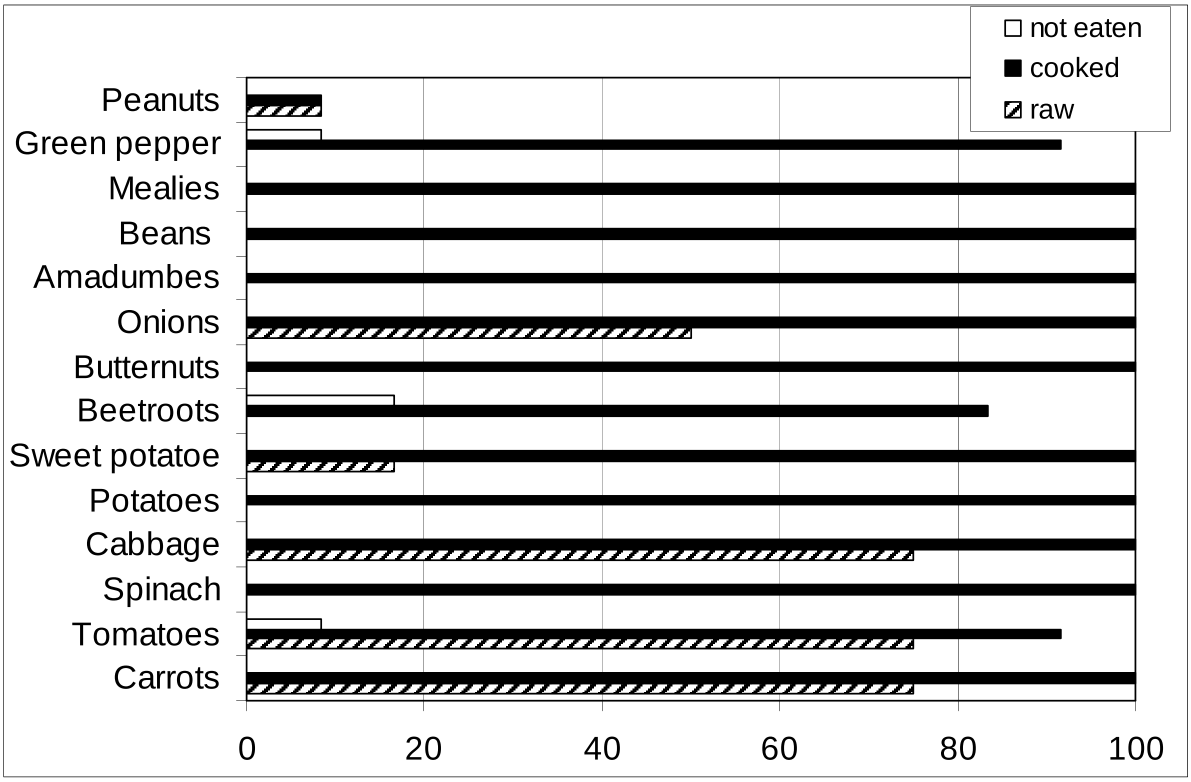


Figure 9-2: Vegetables consumed in % in 20 interviewed households of Magabheni community, investigated in household livelihood interviews.

9.5.2.3 Preliminary farming system design

Based on investigations on drivers, resources and objectives of the farming community and constructive discussions a potential preliminary agricultural design could be developed. The area was fenced and while ongoing discussions and negotiations with farmers, seeds and irrigation water was supplied. With observations on the partly established preliminary system and earlier gathered information potential health, environmental and agronomic risks chould be evaluated as presented in Chapter 5.3. Major aspects of interest for risk evaluation are field size, crop choice, irrigation system and quantity of required irrigation water.

In the first meetings with the community an agricultural area was identified which seemed to be manageable in size for the five active farmers and is not subject of struggle over land claims. The area of 125 x 85 m is being fenced, a small pack shed with concrete floor is build and a container for storage of working material is supplied. Pack shed, container, walk ways and vertigo grass which was formally planted along contour lines of the upper part of the field to avoid erosion takes up approximately 600 m². Consequently, the total arable area is about 1 ha.

Crop choice

Crops planted in Magabheni household vegetable gardens are assumed to be feasible to plant since agricultural skills are available amongst cooperative members and households of the community are interested in consuming and purchasing them. Figure 9-2 indicates options for marketable crops among community households based on assessed consumption patterns. The cooperative has no financial capacity of purchasing seeds and seedlings and is consequently dependent on initial governmental supply. Khanyisa Projects assists several communal agricultural projects in eThekwini and no special treatment was considered for Magabheni. Supplied seeds and seedlings were the crops of the season and supplied to all supported gardens during this time of the year. In June 2009, 2000 seedlings of Cabbage, Carrots, Spinach and Beetroots (500 each) were supplied to the cooperative garden and planted rapidly. Beginning of July 400 g Green beans, 400 g Spinach, 130 g Beetroot, 100 g Onion, 30 g Carrot and 130 g Cabbage seeds were supplied and planted. Farmers were satisfied with the amount of seeds they received in this early stage of the project and could plant approximately 1/3 of the fenced field (1 ha) with it.

Irrigation System

An electrical pump in a pump house at the treatment ponds and underground, partly damaged supply pipes over the old project area are assets of the old irrigation project left on site. Additionally the cooperative has a large amount of micro sprinklers and overhead impact sprinklers in stock.

Khanyisa Projects proposes to establish a partly new irrigation system which better fits better to investigated requirements and capacity of the farming community.

The objective is to establish a supply system where farmers can retrieve water on-demand on the field without complicated operational procedures which was found to be a shortcoming in the old centrally managed irrigation system design in 2003. A gravity feed system is proposed and established where operational irrigation water storage facilities on the hill approximately 10 m above and in 150 m distance to the field are filled by operating the pump at the treatment ponds. Four closed storage tanks made out of plastic with a total capacity of 20 m^3 are connected to a permanently filled distribution system dispread over the agricultural site with several outlet valves. Farmers are able to withdraw required irrigation water spatially independent on the field by opening a corresponding valve. The fact that in this system the pump is only operated temporarily on full capacity to fill the tanks (approx. 20 min) and not during the whole irrigation time implicates potential energy/cost savings of pumping.

Supply of first seedlings was dated approximately six weeks before installation of gravity tanks with on-demand supply system was completed. During the period without irrigation water supply, first irrigation was performed with a hose connected to a water tab with broken water meter of one of the close by houses. After the gravity feed supply system was installed irrigation was continued by hose. It could be observed that irrigation of the whole field was done daily on the end of the working day (if no precipitation) by hose. Irrigation was mainly performed by children of the cooperative members (6-14 years old) since it is rather work intense. It was observed that dependent of the irrigator either the whole plant (including leaves) or only the ground around was watered. The amount of applied water was also strongly varying and up to irrigator's discretion. In general the hose was held in approximately one meter height and causes a splash effect on the ground or irrigators disperse water by placing a thumb on the hose outlet.

During discussions, cooperative members stated they would prefer an automatic irrigation system to reduce labour input. For a small proportion of land planted with cabbage, micro sprinklers were connected to the gravity feed system and ran almost the entire day, since pressure is too low in the gravity feed system for proper operation. Nevertheless it could be observed that the thin stream of water from the slowly turning head was watering also the leaves of the cabbage. Khanyisa Projects took the decision to wait with the choice on final irrigation method till the assessment of potential health risks is performed. Until then irrigation is continued by hose.

As preliminary considerations for the choice of irrigation method, findings from literature study on feasible irrigation methods for wastewater irrigation presented in Table 5-13 can be used. Micro- and overhead sprinklers seem to not be appropriate for effluent irrigation but will be considered in the evaluation of health risks to illustrate outcomes to farmers who favour the use of the available sprinkler system.

Evaluating possible alternative irrigation methods suggests establishing either furrow or subsurface irrigation. For Magabheni furrow irrigation is considered to be the best option since it is:

- cheap because of no input of external material,
- the amount of irrigation water applied is directly visible to farmers,
- the required knowledge can be taught by local agricultural trainers since furrow irrigation with raised beds is popular within smallholder farming in eThekwini,
- furrows parallel to contour lines can avoid surface runoff and erosion on the partially sloping site,
- in the rainy season furrows keep raised beds well drained,
- farmers can access their plots easily without kneel down,
- contaminated irrigation water has a long ground passage before it reaches the plant roots and does not come in contact with the above ground plant surface,

- it can be operated with limited losses to deep percolation due to low permeability of the soil,
- for irrigation with poor quality water or wastewater furrows show good performance and are robust against operational problems and require minimal maintenance (Crites et al., 2000).

The shortcoming of furrows is that the construction requires relatively high labour inputs, but this has to be done only once if maintained properly over the years.

Choice of reference crop

For calculation and evaluation of risks attached to irrigation with treated wastewater a reference crop is used. Calculations of risks are linked to the amount of applied irrigation water and specific characteristics of the irrigated crop. In Magabheni a large variety of crops might be planted. The scope of this research restricts calculation of possible scenarios for all crops. Cabbage is chosen as reference crop for following reasons:

Cabbage is desired to be produced by farmers because it is comparatively easy to market.

As presented in Figure 9-2 100 % of the households in the Magabheni community consume Cabbage. The crop is assumed to be robust at transport, can be stored comparatively long and achieves a relatively high price in marketing.

In terms of crop water requirements, cabbage has a very high water demand and long growing phases (FAO, 1998).

Compared to other crops cabbage carries a relatively high potential health risk for consumers. It is exposed to a high amount of irrigation water due to long growing phases and high crop water demand. The crop has a high surface area for contamination with pathogens and its funnel shape and coarse leave structure retains potentially high amounts of applied water. It is grown directly on the ground and consumed often raw as salad (Figure 9-2). At best it is washed before consumption, but can not be peeled.

For further calculations, only cabbage will be used as reference crop to calculate a worst case scenario.

Irrigation Requirements

Calculation of irrigation demand of the community garden, as relevant aspect for potential risks resulting from effluent irrigation, requires some data input. Climatic conditions of the area are described in subchapter 5.1.5. The calculation procedure for crop water demand of specific crops is described in subchapter 5.2.2.1. Crop water demand of cabbage as reference crop as justified above is estimated in the following. For simplification in calculation, the moisture holding capacity of the soil is disregarded and only total irrigation water requirements are considered.

Table 9-1 presents the length of crop development stages in days for cabbage as found in FAO (1998). Figure 9-3 presents the correlation of crop development stages with the K_c value. Evapotranspiration can be calculated with K_c and ET_0. In Table 9-2 $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ values from FAO (1998) for different development stages of cabbage are presented with a calculated estimation for average values between the maxima in order to estimate K_c of crop development stage and late season.

Table 9-1: Lengths of crop development stages [days] for cabbage (FAO, 1998: Chapter 6, Table 11)

Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total
40	60	50	15	165

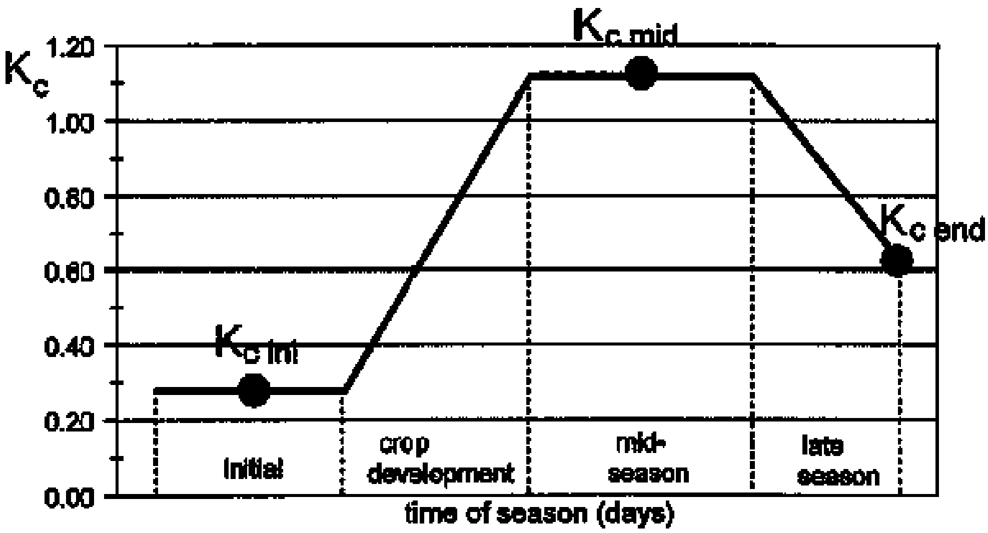


Figure 9-3: Crop coefficient curve (FAO, 1998: Chapter 6, Figure 34).

Table 9-2: Crop coefficients Kc for different development stages of Cabbage for use with FAO ET_O (FAO, 1998: Chapter 6, Table 12) and calculated values for development- and late- season.

$K_{c\ ini}$	$K_{c\ dev}$ (average of initial and mid)	$K_{c\ mid}$	$K_{c\ late}$ (average of mid and end)	$K_{c\ end}$
0,7	0,88	1,05	1	0,95

The review of crop information on cabbage provided by the FAO [10] and observations on planted cabbages in Magabheni community garden allow the assumption that cabbages with approximately 2 kg heads are grown. These would require a corresponding individual plant space of about 0,29 m² per cabbage; consequently 35000 cabbages can be grown on one hectare [10].

Climate data presented in subchapter 5.1.5 enable a worst case calculation for maximum irrigation requirement per head of cabbage in the driest cropping season of the year. The calculated irrigation requirements represent water required by the plant and disregard application efficiency of the specific irrigation method (Table 9-3).

Table 9-3: Calculation of Irrigation requirements per head of cabbage in the driest season of the year.

Month [two weeks]	Mar II	Apr I	Apr II	May I	May II	Jun I	Jun II	Jul I	Jul II	Aug I	Aug II
ET0 [mm/d]	3	2,6	2,3	1,9	1,6	1,4	1,3	1,3	1,5	1,7	1,9
Rainfall [mm/d]	3,5	2,6	2,6	1,5	1,5	0,9	0,9	0,8	0,8	1,1	1,1
Growing stage	L_{ini}	L_{ini}	L_{ini}	L_{dev}	L_{dev}	L_{dev}	L_{dev}	L_{mid}	L_{mid}	L_{mid}	L_{late}
Kc	0,7	0,7	0,7	0,87	0,87	0,87	0,87	1,05	1,05	1,05	1
ETc	2,1	1,8	1,6	1,7	1,4	1,2	1,1	1,4	1,6	1,8	1,9
Net Irrigation Requirement [mm/d]	-	-	-	0,2	-	0,4	0,3	0,6	0,8	0,6	0,7
Area per head [m²]	0,29										
Irrigation Requirement per head [L/d]	-	-	-	0,058	-	0,100	0,076	0,169	0,229	0,169	0,202

For the evaluation of health risks by consumption of crops, the developed QMRA scheme shows that the volume of applied irrigation water is crucial particular in the last weeks before harvest. For the calculation of health risks, a worst case scenario of two month period with full irrigation requirements due to no rainfall in the last phase before harvest is assumed (Table 9-4).

Table 9-4: Irrigation requirements per head of cabbage [L/day] two month before harvest without rain.

Month [two weeks]	Jul I	Jul II	Aug I	Aug II
Irrigation requirements per head of cabbage [L/d]	0,390	0,450	0,510	0,543

Using the observation that approximately 1/3 of the total arable area of 1 ha was planted the current total daily irrigation water requirements of the Magabheni site can be calculated (Table 9-5).

Table 9-5: Irrigation requirements for reference crop cabbage per ha and per planted area, calculation according Table 9-3.

Month [two weeks]	Mar II	Apr I	Apr II	May I	May II	Jun I	Jun II	Jul I	Jul II	Aug I	Aug II
Irrigation requirements per ha [m³/ha·d]	-	-	-	2,0	-	3,5	2,6	5,9	8,0	5,9	7,1
Irrigation requirements for the planted area [m³/(1/3)ha·d]	-	-	-	0,7	-	1,2	0,9	2,0	2,7	2,0	2,4

Due to information given by cooperative members operating the pump to fill the operational storage and observations, the assumption is made that filling is done careful and only 2/3 of the total storage capacity is in use. The correlation of adjusted volume and time yields in an average amount of total supplied irrigation water for the planted 1/3 ha of 3,8 m³/day. Comparing this estimation of applied irrigation water with the calculated crop water requirements from Table 9-5 allows the conclusion that in July and August 30-50% excessive irrigation water was applied. Reasons might be losses due to over-irrigation and subsequent deep percolation, evaporation or drainage.

The found water losses are described as field application efficiency (E_a). In theory E_a is affected by thy type of irrigation system, soil typed and the skill of the farmer (Vuren, 1992; Dries and Gerbrandy, 2005).

Equation 7

$$E_a = \frac{Volume\ of\ rain\ deficit\ in\ croped\ area}{Volume\ of\ water\ applied\ to\ the\ croped\ area}$$

The application efficiency of $E_a = 0{,}5 - 0{,}7$ in the Magabheni case can be evaluated in relation with usual application efficiencies for different scenarios presented in Table 9-6 (Dries and Gerbrandy, 2005). Since mainly children irrigate with abundant water the skills to irrigated with high efficiency are assumed to be low due to few experience. When a formal irrigation method is introduced (considering furrow irrigation or sprinkler irrigation) E_a is expected to rise over time with more experience on irrigation to approximately 0,6 - 0,7.

Table 9-6: Field application efficiencies from different studies (source: Dries and Gerbrandy, 2005:6-73).

Field application efficiency (Ea)

		USDA	US(SCS)	ICID/ILRI
Surface methods:				
- soil type	- light soils	0.55		
	- medium soils	0.70		
	- heavy soils	0.60		
- irrigation method	- graded border		0.60 - 0.75	0.53
	- basin and level border		0.60 - 0.80	0.58
	- contour ditch		0.50 - 0.55	
	- furrow		0.55 - 0.70	0.57
	- corrugation		0.50 - 0.70	
Subsurface			up to 0.80	
Sprinkler	- hot, dry climate		0.60	
	- moderate climate		0.70	
	- humid, cool climate		0.80	0.67
Rice				0.32

9.6 Brief Research Proposal on Magabheni Irrigation project.

Date: 17.6.2009

By: Wolf Raber and Sandra Hildbrand

Background:

Intended wastewater reuse for irrigation at the Magabheni project is threatened by occasional “high” E-coli counts of wastewater treatment pond effluent. Decision makers are concerned about possible health risks for farmers and consumers.

Problem Statement:

Health risk origin from effluent use for irrigation is not discussed scientifically. There is a lack of experience in estimating health risks and defining appropriate interventions along the whole production chain to reduce health risks.

Concepts:

The *production chain* in the case of consumers is: Wastewater generating community – raw sewage – Pond treatment (four pond system) – irrigation water storage – irrigation – crops – harvest – crop processing – market – preparation – consumption. In case of health risk for farm workers the chain stops accordingly at the process of irrigation.

Quantitative microbial risk assessment (QMRA) is a four-step process comprising of hazard identification, exposure assessment, dose-response modeling and risk characterization.

Household Assets are

- Natural capital: land and water rights / access
- Human capital: labor power, Skills to plant certain crops with certain irrigation techniques, household age and occupation structure
- Financial capital: Money available
- Physical capital: house, equipment, animals, land
- Social network: potential customers for crops, external labor, network of trust for various inputs
- Capital of the cooperative: capacity to access external input in terms of training, material, finances, services

Methodology:

Conduct a Household Livelihood Assessment by interviews in households of cooperative and normal community members in Magabheni. Complement information on farming praxis by observations in the community garden. Determine cooperative objectives including preferred farming system (irrigation techniques, crop choice, agricultural practice, aspired farm size) and assets of households and cooperative.

Assessing the health risk for farmers and consumers by the intended farming system though quantitative microbial risk assessments (QMRA) on basis of the WHO 2006 Guidelines, Volume 2: Wastewater Use in Agriculture. For this step appropriate indicator organisms have to be found through literature review.

Sketch potential intervention strategies along the production chain in order to reduce potential health risks down to an acceptable level. The wastewater treatment unit will receive interest but also interventions by farmers themselves like irrigation techniques, water and land management or crop choice will be considered.

Make recommendations for efficient, cost effective and social sound measures to reduce health risk on basis of farmer objectives, assets, possibilities and constrains.