Judgment under Uncertainty;
A Probabilistic Evaluation Framework for Decision-Making about Sanitation Systems in Low-Income Countries

Shirin Malek Pour

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TU Delft
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Challenge the future

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A Probabilistic Evaluation Framework for Decision-Making about Sanitation Systems in Low-Income Countries

MSc Thesis for the Degree of Master of Science in Civil Engineering

Shirin Malek Pour

Graduation Committee:

Prof. dr. ir. Jules van Lier

Prof. dr. ir. Francois Clemens

Dr. ir. Jeroen Langeveld

Ir. Laura Talsma

July 2012

Sanitary Engineering Section, Water Management Department

Faculty of Civil Engineering and Geosciences

Delft University of Technology

The Netherlands

Preface

This thesis has been performed towards fulfilment of the requirements for the degree of Master of Science in Civil Engineering at Delft University of Technology (TU Delft).

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Summary

Sanitation, as described by the World Health Organization (WHO), refers to the provisions of facilities and services for the safe disposal of human urine and faeces.

On the outset of the 21st century, inaccessibility of 40% of the world's inhabitants to sanitation facilities sounds like an international shock. This literally means that 2.6 billion people in the world still rely on a bucket, a bush or a backstreet for excretion.

As an inheritance of the colonial period, for years emphasis was made on copying the western sanitary achievements by trying to provide sewerage coverage in developing countries. It was revealed later that the required investments in conventional sewerage systems exceed the allocated financial resources in many of the low-income countries and these sanitation options are not likely to reach the huge poor populations in those regions.

Facing the failure of conventional solutions in many cases, alternative solutions (e.g. small-scale systems) were proposed for developing countries, but did not remain protected from criticisms either.

Among all available sanitation options, decision makers and planners in developing regions of low-income countries have to encounter the dilemma of which path to choose. Low-income countries, due to their vast socio-economic inhomogeneity, are more complex target locations for selection of appropriate sanitation options. The dynamic situation in these regions with the rapidly growing populations (especially in the urban settings) and the changing socio-economic structures make decision-making a more fragile process. Technically, all options that are required to deal with the global sanitation crisis seem to have been developed already. However, the challenge remains in selection and implementation of the appropriate technologies in a way that the desirable outcomes would be resulted. Some decision-making support tools have been developed so far to address this problem by assisting the decision makers in their challenging task; an attempt that may be described as: *The low-sighted leading the clueless, with a map that keeps changing.*

In the existing sanitation decision-making support tools, evaluation of sanitation options is performed based on predicting the outcomes that best represent a sanitation system. This kind of 'representativeness' is often used to feed the intuitive judgment with no or little regard to the uncertainties that lie in the predictions. The 'illusion of validity' often dominates the evaluations, neglecting the factors that limit the predictive accuracy and the fact that the expected outcomes do not always occur in practice.

This thesis recognizes the need for decision-making support frameworks to assist the planners and decision makers (especially in low-income countries) in selecting sanitation options that are more likely to be the appropriate options within their local context. It adopts a new approach by taking into account the real world examples from executed sanitation facilities and develops a

probabilistic evaluation framework in which sanitation options are assessed based on the probabilities that specific outcomes occur in practice. Absolute judgments are replaced by probable assessments as this approach tries to keep its distance from making the uncertain certain.

Although there may be a hidden consensus that quantification of occurrence probabilities for various outcomes of sanitation options is not always possible, some quantification methods are developed and presented in this thesis for all the assessment criteria. Nonetheless, these methods shall not be regarded as the only ways of quantifying the assessments. They are rather presented in order to show that, in contrast to the first impressions that one might get, it is not impossible to quantify such assessments; an impression that may have been the major drive for turning into qualitative judgments by over-simplifying the reality.

Following the probabilistic evaluation of sanitation systems, measures to improve the performance of various options with regard to the assessment criteria are also presented in the present document. Channelling the decisions in such a way that the risks of negative outcomes of sanitation facilities would be reduced is specifically addressed in this work.

In the end, the developed evaluation approach is performed for the low-income unplanned slum settlement of Nyalenda in Kisumu, Kenya based on limited available data about this region in literature. This case study proves that while a sanitation option may be known for fulfilling a certain task by definition, through a probabilistic evaluation it may be revealed that the site conditions are not likely to allow the expected outcome to occur in practice and as a result this option would have no (or even less) priority among other options.

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1. An Introduction to the Global Sanitation Challenge

Sanitation, as described by the World Health Organization (WHO), refers to the provisions of facilities and services for the safe disposal of human urine and faeces.

In the 21st century, lack of access to sanitation facilities by 40% of the world's population sounds like an international shock. This means that about 2.6 billion of the world's citizens, majorly in developing countries, still rely on a bucket, a bush or a back street for excretion (Black and Fawcett, 2008). About 2.2 million people per year die out of diarrheal diseases (WHO, accessed 2012), for which presence of faecal pathogens in the humans living environment is mainly responsible.

In the urbanizing world with an intense population growth that happens even at a faster pace in low-income countries, the sanitation challenge gets more complex. From 1990 to 2006, about 1.1 billion people in the developing countries gained access to improved sanitation facilities (UNDESA, 2009). However, the number of people without access to sanitation facilities has remained unchanged over these years owing to the rapid population growth that exceeded the sanitation coverage rate.

The history of sanitation is as old as the history of human settlements. Archaeologists have discovered the remaining of sanitation networks from some of the earliest civilizations. The Harappans, who were the citizens of the Indus basin (today's Pakistan, northwest India, eastern Afghanistan and southeast Iran) in 2500 BC had a highly developed sewer network made of brick in which wastes from each house was collected (Black and Fawcett, 2008). Similar sewer and drainage systems have been discovered from the palaces of the Minoan civilization in Crete (Black and Fawcett, 2008).

Contrary to the advanced sanitation provisions in some of the early civilizations, during the Middle Ages and early modern times in most European cities, excreta were freely dumped into the streets. While the streets of Paris stank from the chamber pots that were thrown out of the windows (Black and Fawcett, 2008), a Frenchman visiting a country house in England in 1784 writes in his logbook that he found it indecent that "The sideboard is garnished with the chamber pots, in line with the common practice of going to the sideboard to pee, while the others are drinking." (François duc de La Rochefoucauld, translated and edited by Scarfe, 1988).

Development of water flush toilets in Europe and their scale up was accompanied by the industrial revolution in Britain in the late 18th and early 19th century, which transformed the standards of living together with raising the incomes. Private sector manufacturers responded to this change by developing new items, including the sanitary wares, for the privileged classes who were able to pay them. However, development of sewer systems did not occur simultaneously, resulting in the content of flush toilets ending up in the environment. The 'Great Stink' was a time in the summer of 1858 in London, when the smell of untreated human waste became very strong in the Thames. This event and the outbreak of cholera, along with the previous campaigns on sanitary reforms led to a sanitary revolution in Britain and then in other parts of Europe and North America. Nonetheless, the complete transformation of the urban living into something piped and sewered among all social classes (and not only the privileged ones) took over six decades (Black and Fawcett, 2008). It took time until the concept of public health was well realized and it became clear to the higher classes that they were also threatened by diseases spreading among the poor. This was the time when the states got involved to deliver the human waste disposal services to the poor, regardless of their ability to pay, in favour of the public health (Black and Fawcett, 2008).

In the developing world, the sanitation challenge is still on-going. For years, it was an inheritance of the colonial period to put emphasis on copying the western sanitary achievements by providing sewage coverage in developing countries (Oosterveer and Spaargaren, 2010; Black and Fawcett, 2008).The results from a World Bank 2-year research project on Appropriate Technologies for Water Supply and Sanitation in Developing Countries (1976-1978), followed by declaration of the 1980s as the International Drinking Water Supply and Sanitation Decade by the member countries of the United Nations, led to a global realization about the alternative sanitation options. It was revealed that the required investments in conventional sewage systems exceed the available financial resources in low-income countries and these sanitation options are not likely to reach the big poor populations in those regions (Kalbermatten et al., 1982; Rao, 1986; Mara, 1996).

In frustration of the failure of the conventional solutions, that require high financial and institutional arrangements, alternative solutions of small-scale and decentralized systems were proposed for developing countries. Decentralized sanitation and reuse systems gained attention, partly in opposition to centralized ones (Mels et al., cited in Oosterveer and Spaargaren, 2010), but still remained as a second-best option useful in situations where the finances, technical and organizational capacities were severely limited to implement centralized options (Oosterveer and Spaargaren, 2010).

While the centralized versus decentralized sanitation options debate is continuing, decision makers and planners in developing regions of low-income countries face the dilemma of which path to choose. The concept of Modernized Mixtures (MM) introduced by Spaargaren et al. (2006), tries to keep distance from these debates and aims at combining the best features of centralized and decentralized systems. It uses a mix of scales, strategies, technologies, payment systems and decision-making structures, to create a better fit within the conditions for which they are designed (Hegger, 2007; Oosteveer and Spaargaren 2010; Letema, 2012).

As various technologies that are required to address the global sanitation challenge seem to be already available (Loetscher and Keller, 2002; Tilley et al., 2010), the main challenge remains in selection and implementation of appropriate technologies in a way that the desirable outcomes would be resulted. Low-income countries, due to their vast socio-economic inhomogeneity, are more complex target locations for selection of the appropriate sanitation options (Loetscher and

Keller, 2002). The dynamic situation in these regions with the rapidly growing populations (especially in the urban settings) and the changing socio-economic structures (for examples on this refer to the statistics presented in United Nations Statistics Division website at http://unstats.un.org over the past years) makes decision-making a more fragile process. In most low-income countries, owing to the lack of structurally recorded environmental and social data, lack of sufficient well-established management institutions, the diversity and the dynamics in the socio-economic conditions, and on top of all, due to limited financial resources, the planners inevitably face a huge uncertainty in their decisions.

This thesis recognizes the need for decision support frameworks to assist the planners and decision makers (especially in low-income countries) in selecting sanitation systems that are more likely to be the appropriate options within their local context. It adopts a new approach by taking in to account the uncertainties that lie in the decisions to be made, and keeps its distance from making the uncertain certain. Rather, it tries to develop a probabilistic approach in which the evaluation of sanitation systems is done not based on intuitive judgments, but with respect to the probabilities that hide in each and every assessment steps.

2. A Review on Some of the Formerly Developed Sanitation Decision-Making Support Tools

To address the complex global sanitation challenge, there is a need to identify, evaluate and choose technologies or approaches that can best deal with the sanitation problems and requirements of the communities. To assist those who need to make decisions and implement such technologies and approaches, a variety of support resources have been developed. These support resources may include design specifications, technical briefs, technical guides, decision-making support tools and any other information source that can help the decision makers who are finding ways to meet the sanitation requirements of their societies (e.g. Franceys et al., 1992; UNICEF, 1997; DWAF, 2004; Huuhtanen and Laukkanen, 2006).

A decision-making support tool is a subset of the support resources that combines the information from the existing situation with the information on available technologies and approaches. It compares and contrasts various options and assists the decision makers in choosing the most appropriate available option for a specific situation (Palaniappan et al., 2008). The comparison and evaluation of different options may be carried out with regard to technical, social, institutional, legal and financial criteria. However, not all decision-making support tools cover all these aspects, but rather different tools may focus on one or a few of the above-mentioned aspects. In the past, several decision-making support tools to assess the sanitation options have been produced in various formats such as flow diagrams (algorithms), decision tables and checklists (Loestscher and Keller, 2002).

Palaniappan et al. (2008), in a systematic review on the existing decision support resources in water, sanitation and hygiene sectors, identified 120 resources that could provide decision makers with some sort of their required information. They claimed that out of the 120, only 18 could resemble a decision-making support tool, with 12 of them relevant for the sanitation sector. The large number of the decision support resources indicates that it has been widely realized that there is a need to support the selection process and that there is actually a good amount of information available to the decision makers. However, the small number of the decision-making support tools indicates that the available information is scattered and is often not provided systematically to respond to the specific requirements of the underserved situation.

Kalbermatten et al. (1982) was one of the firsts to develop a planning and design manual for sanitation alternatives in low-income countries. This manual documents the findings of the World Bank 2-year research project on Appropriate Technologies for Water and Sanitation in Developing Countries (1976-1978), in which it was revealed that the conventional sewage systems are not likely to reach the poor communities with the available financial resources and that there is a need for sanitation alternatives in developing countries. In this planning manual, which may resemble a decision-making tool, different sanitation options are compared qualitatively with regard to various criteria such as ease of construction, water requirement, institutional requirements, costs, reuse potentials, etc. A table of descriptive comparison for sanitation technologies is presented. Moreover, an algorithm for selection of sanitation technologies is developed through which the decision makers will be guided to a specific sanitation technology after answering *Yes* or *No* to a set of questions regarding the underserved location and situation (e.g. Is there water available? Is the soil permeable? Is the level of the groundwater table lower than a certain value? Are the facilities maintainable? etc.). Such algorithms that end up with a sanitation option through a series of Yes-No questions to be answered by the planners have been also developed by other authors including Winblad and Kilama (1985), Mara (1996) and Tayler (2000).

The main problem associated with using such algorithms in selection of sanitation options lies within the certainty in the *Yes* or *No* answers that shall be given to the questions before moving to the next stage in the selection process. While such flow charts deal with absolute answers, the reality consists of relative situations in which a certain Yes or No may not exist, but rather exists a range a probabilities and proportions. For instance, the answer to the question: 'Are the facilities maintainable?' may not be a simple yes or no, as both the maintenance activities and the required resources to manage them have a complex structure that is influenced by various factors. Even in developed countries with established institutions and more easily accessible financial resources, there is an extent to maintainability of facilities and reliability of services and an answer that represents a 0% or 100% situation may be misleading and not representative of the reality. Although such algorithms may channel the decisions and provide some assistance for a general view on possible sanitation options, but their leading to a choice of sanitation type is controversial. Perhaps this problem was even realized by some of the developers of such algorithms, as Mara (1996) states: "An algorithm like this one is useful in that it makes you answer questions that you may not have thought of and it helps guide you to select what is usually the most appropriate sanitation option. ", and Tayler (2000) states: "This flow diagram is meant for guidance and the figures and recommendations given are not intended to be absolute."

Another type of decision-making support tool works with rating the available options against various criteria in the format of an assessment table (multicriteria analysis). The ratings of different options from different criteria could be aggregated in the end, to come up with the most appropriate sanitation option that gains the highest score among all.

NETSSAf aid (Zurbrüegg and Tilley, 2007) is a support resource that produces an assessment table for a wide range of sanitation options, from toilet facilities to transfer and treatment. It evaluates the facilities with regard to various criteria and uses a qualitative assessment in which ++, +, o, - and - - signs are used to indicate that a criterion is very well fulfilled, fulfilled, is neutral, is not fulfilled or is not at all fulfilled by a sanitation facility. The use of these assessment tables is easy and the reader can review the overall performance of different options at a glance.

The shortcoming associated with assessment tables as developed in NETSSAF aid is due to the qualitative judgement of the options with no clear distinctions between the devoted ratings. For instance, the boundary between the - and - - signs is not clear as it is controversial to put a clear distinction between technologies that 'do not fulfil' or 'do not at all fulfil' a criterion. Furthermore, such assessment tables use technology-specific criteria for evaluation and therefore the results of the evaluation is always the same for the same technologies regardless of the underserved situation and the site-specific conditions. This lack of site specificity does not even satisfy the definition of a decision-making support tool in which the information from the existing location shall be combined with the technology-specific data.

There are other decision-making support tools that also use a multicriteria analysis of sanitation options, but tend to quantify the judgements by numerically scoring and ranking the assessments. SANCHIS (van Buuren, 2010) is a sanitation decision-making support tool that formulates the entries to the assessment matrix as a numerical value, instead of using qualitative judgements. The core of such a multicriteria analysis is trading off the disadvantages with respect to some criteria against the advantages with regard to other criteria. The trading-off method used in SANCHIS is SMARTS (Simple Multi Attribute Rating Technique using Swings) (Edwards and Barron, 1994). In this method the raw performance values are transformed to common dimensionless values that are used to score the options with regard to different criteria. Assume that the investment cost of sanitation options is an assessment criterion and there exists 3 options with quantified investment costs of 950,000- 1,000,000 and 1,050,000 Euros. In SANCHIS the lowest investment cost among the options (i.e. 950,000 Euros) will be given a value of 100 (as low costs are always preferable) and the highest investment cost (i.e. 1,050,000 Euros) will be given a value of 0. Through linear interpolation the other sanitation option with investment cost of 1,000,000 Euros will get a score of 50. The same way of scoring will be performed for the sanitation options with regard to all the other criteria.

Once the score of sanitation options with respect to all the criteria is specified, the assessment criteria shall be weighed. In SMARTS, the weighing is a 2-step process in which:

1: the criteria are ranked based on their importance (from 1 to n, where 1 is the rank of the most important criterion and n is the total number of the criteria used for assessment) and,

2: the weights are assigned to the criteria on a 0-100 scale (swing weighing), with the 1st rank from step 1 receiving a weight of 100 and the other ranks receiving any value between 0 and 100 based on the judgement of the assessors.

According to the SMARTS method, the weight given to a criterion should not only represent the importance of that criterion among others, but also the difference of the given values to different options with respect to that criterion shall be taken in to account. In the above example with the investment costs as a criterion, if the cost difference among the available options is small (e.g. 950,000, 1,000,000 and 1,050,000 Euros for 3 sanitation options that are assessed) the importance of the investment costs as a factor in decision-making shall be low. This consideration is built in to SMARTS by application of swing weighing.

When the weighted scores of the sanitation options with regard to all the criteria is calculated, the total score of the sanitation options will determine the selection.

The strength of a quantitative multicriteria decision analysis as introduced in SANCHIS is in using quantified values that should be literally estimated before decision-making, in contrast to qualitative judgements where the rankings are rather vague. Another advantage of methods like SANCHIS is that they take into account both the technology-specific and the site-specific criteria and therefore the assessments are localized for the underserved conditions, which increases the likelihood of appropriate decisions for each specific situation.

The weakness of multicriteria decision analysis methods like SANCHIS however, lies in using single certain values for scoring of the options while the reality often deals with a range of possible values. The values for investment costs as presented in the above example for instance, are not fixed amounts but rather consist of a range of uncertainty. This is often admitted by the developers and users of such tools, as van Buuren (2010) suggests running a sensitivity analysis considering the uncertainties in the performance scores and the criterion weights in order to gain insight into the impact of using different values on the total score.

Another remark that could be made on SANCHIS is with regard to its emphasis on the stakeholders view in decision-making which may leave little room for new technologies and systems of which stakeholders are not well aware.

Computerized decision-making support tools have also been developed to facilitate the selection process for sanitation systems. Water and Wastewater Treatment Technologies Appropriate for Reuse Model (WAWTTAR) is a computer program (Finney and Gearheart, 1998) which allows users to input data from local conditions in to the program while it evaluates the various water and wastewater treatment options.

SANEX (Loetscher and Keller, 2002) is a recent computerized decision support tool in sanitation sector which covers low-end facilities such as latrines, and that addresses sanitation problems in developing countries. It also uses a multicriteria analysis for rating the available alternatives with regard to different criteria. In SANEX, the user is asked a series of questions. The answers given to the questions determine the scores of the options that are being assessed. The input scores to the criteria may be Boolean, discrete or continuous, but are standardized based on a 0 to 1 rating where 0 represents the worst and 1 represents the best outcome. For instance, a question asked in the program is: Is fuel available? This criterion affects the suitability of systems that rely on emptying by the trucks. The input to this criterion in the program will be Boolean. The answer No assigns a value of 0 and the answer Yes assigns a value of 1 to this criterion. Another question with a continuous input score in SANEX is with regard to the willingness of the community to participate in the sanitation systems development. The program asks the question: How is beneficiaries' willingness to participate? The input is qualitative and may be very low, which assigns a value of 0 as the score to this criterion, or very high that assigns a value of 1 to this criterion. Values between 0 and 1 may be used to indicate the situations in between the very low to very high participation. In the end, all the ratings will be aggregated to result in a final score for sanitation options with respect to all the criteria.

Although SANEX succeeds in creating a user interface which is lacking in many decision-making tools, the rating model is not transparent to the users and they often find it difficult to relate the ratings to their inputs (Loetscher and Keller, 2002). The *Yes* or *No* answer to some of the questions is the act of making the uncertain reality certain. The existence of a range of possibilities and values is neglected in this model. Moreover, the qualitative inputs (such as very low, low, etc.) are vague and assigning any of these qualities to the criteria may be controversial and the distinctions among the qualities are not specified, but rather depend on the personal judgement of the user.

An overview of the formerly developed sanitation decision-making support tools is presented in Table 1. Apart from the weaknesses and the shortcomings of different sanitation decision-making support tools as already discussed in this chapter, in most of these tools more emphasis is devoted to making a choice rather than channelling the decisions in such a way that the likelihood of desirable outcomes is increased. When the sanitation options are evaluated with regard to different criteria, their performance is often considered as it is and the possible measures to improve their performance is not systematically incorporated in to the decision-making process, while information on these possible measures is readily available in many design guidelines.

Moreover, most of the sanitation decision-making tools lack the provisions for evaluation and monitoring of selected options, with a feedback loop from usage to planning. An interactive process is overlooked in which the users of the technologies could influence or be influenced by the selected technologies, and the technological hardware could be adapted to fulfil the environmental or the socio-cultural requirements. Evaluation and monitoring of the implemented projects with a feedback loop from usage to planning can increase the possibility of appropriate decisions in similar projects and can also provide means for improvement of the already implemented systems.

In this thesis, the attempt has been made to address the shortcomings in the existing sanitation decision-making support tools and to develop a framework through which evaluation of sanitation options is done in a way that the likelihood of sound decisions may be increased. Furthermore, measures to improve the performance of sanitation options with regard to various criteria are presented and evaluation and monitoring of the implemented options is also addressed.

Table 1: Overview of some of the formerly developed sanitation decision-making support tools

<table>
<tr><th>Decision-Making Support Tool</th><th>Developer(s)</th><th>Approach</th><th>Remarks</th></tr>
<tr><td>Algorithm for selection of sanitation technologies</td><td>Kalbermatten et al. (1982)</td><td rowspan="4">An algorithm that leads to a sanitation option through a set of questions which have Yes or No answers</td><td rowspan="4">Certain answers (Yes-No) are required in every stage to move to the next stage in the decision-making process, while the reality often deals with a range of probabilities and possibilities. The result of such algorithms is a certain sanitation option that comes in the end.</td></tr>
<tr><td>Algorithm in "Sanitation without Water"</td><td>Winblad and Kilama (1985)</td></tr>
<tr><td>Technology selection algorithm</td><td>Mara (1996)</td></tr>
<tr><td>Flow diagram in ordering sanitation choices</td><td>Tayler (2000)</td></tr>
<tr><td>NETSSAF Aid</td><td>Zurbrügg and Tilley (2007)</td><td>Multicriteria analysis with qualitative rating of sanitation options against different criteria</td><td>The criteria is technology-specific and the same outcome is always derived regardless of the situation. Distinction among the devoted ratings is vague in such qualitative judgments</td></tr>
<tr><td>SANCHIS</td><td>van Buuren (2010)</td><td>Quantitative multicriteria analysis using SMARTS</td><td>Single values are used for scoring of options and a probable range of values is not directly implemented in the method.</td></tr>
<tr><td>SANEX</td><td>Loetscher and Keller (2002)</td><td>Computerized tool using a quantitative multicriteria analysis with Boolean, discrete or continuous ratings</td><td>The rating method is not transparent to users of the tool. Boolean ratings overlook the existence of a range of possibilities.</td></tr>
</table>

3. Development of a Probabilistic Evaluation Framework for Decision-Making about Sanitation Systems in Low-Income Countries

Making decisions about sanitation systems, like many other decisions, is based on considerations on the likelihood of uncertain events. Tversky and Kahneman (1974) show that people rely on a limited number of heuristic principles that reduce the complex task of evaluating and predicting probabilities to simple judgmental operations. These heuristics, although sometimes useful, may lead to severe and systematic errors as well.

In the existing sanitation decision support resources and decision-making support tools (e.g. SANEX,SANCHIS, NETSSAF; see section 2), evaluation of the sanitation options is mostly performed based on predicting the outcomes that best represent a sanitation practice. This kind of 'representativeness' is often used to feed the intuitive judgment with little regard to the uncertainties that lie in these predictions. In these cases the 'illusion of validity' dominates the evaluations, which as defined by Tversky and Kahneman (1974), means that predictions are done by selecting the outcomes that are most representative of a system, with no or little regard to the factors that limit the predictive accuracy. As one example, in both SANEX and NETSSAF, bio-latrines (biogas digesters) are rated high in evaluations with regard to the resource recovery criterion. This is because biogas digesters are known and are developed for recovering biogas for reuse. However, there are examples from Kenya for instance, where the biogas digesters were built with the intention to replace the firewood stoves with gas cooking facilities, but the digesters were not even connected to any gas consumption facilities, with the produced biogas being vented in to the atmosphere (Binol, 2012; personal correspondence). In another example from application of SANCHIS in decision-making on sanitation facilities in the Ho Chi Minh City in Vietnam (van Buuren, 2010), urine diverting toilets are ranked higher compared to normal flush toilets for the criterion of nutrient recovery. Although this evaluation is correct potentially, in practice there are many examples of urine diverting toilets being implemented but remained without any nutrients recovery due to the missing link between production and reuse (see Letema, 2012 and Carlesen et al., 2008 for examples on this). Under such conditions, rating biogas systems or urine diverting systems high in evaluations, just based on their being representative for resource recovery, without any regard to the actual provisions for resource recovery in practice is an illusion of validity.

In this thesis, the evaluation of sanitation options is done based on the probability that the expected outcomes of selecting a sanitation facility occur in practice, considering the percentage of the population who is likely to be affected by those outcomes. Absolute judgments are replaced by probable assessments in this approach as it tries to keep its distance from simplifying the reality by artificially making the uncertain certain.

The framework, as developed in this thesis, consists of 2 steps:

Step 1: Screening of the sanitation options and eliminating the ones that will not be able to function under the existing situation;

Step 2: Probabilistic evaluation of the sanitation options that pass through the screening stage. This will be done by quantifying the probabilities of specific outcomes to an extent that the available data permit.

In this probabilistic evaluation, in contrast to other methods, there is a consistency in the change of the risk levels versus the assessment criteria. For instance, in SANEX, considering the risk of groundwater pollution from sanitation facilities, it is mentioned that: "If groundwater is abstracted locally, alternatives that rely on soil absorption (e.g. latrines) are only feasible if the groundwater table is more than 5 m below the ground surface." (Loetscher and Keller, 2002). Following such a certain judgmental approach, if groundwater table is 4.9 m below the surface, facilities that rely on soil infiltration must be eliminated; while in a situation where the groundwater table is present at 5.1 m below the surface, the same options will be considered. But how different would the real risks be in both situations? In a probabilistic evaluation method as developed here, the sudden shifts in defining the risk levels are replaced by consistent functions that relate the risk levels to the assessment variables (groundwater table level in the above example).

In the framework as developed in this thesis, following the probabilistic evaluation of sanitation systems, measures to improve the performance of various options with regard to the assessment criteria are also presented. Channelling the decisions in such a way that the risks of negative outcomes of sanitation facilities would be reduced is specifically addressed in this work.

It should be noted that financial concerns and the investment and operational costs of the sanitation facilities are not included in the probabilistic evaluation of the options in this model. Rather, technical and social matters are specifically addressed, in order to present a picture of the probable 'function' of the sanitation facilities. While it is very well acknowledged that capital and operational costs play a major role in the final decisions to be made, they may be assessed as a separate factor.

3.1. Defining sanitation systems and their objective

Prior to developing a framework to assist decision-making on sanitation systems, their definition and their objectives shall be specified.

Following the definition of WHO for sanitation (see chapter 0), sanitation systems would refer to facilities and services developed for the safe disposal of human urine and faeces. In this thesis, the objective of sanitation systems is defined as providing some level of protection against direct contact with human wastes, with an outlook for improvement of public health of the underserved society.

In planning to provide sanitation facilities for the communities, it is a common pitfall to stay focused on toilet facilities, as they materialize the relation between users and sanitation service providers (van Vliet et al., 2010). However, a sanitation system shall entail the whole sanitation chain and not just the individual components of the system such as toilet facilities. The sanitation chain may be defined as a system which starts with toilet facilities and is linked to collection, transfer and treatment of human wastes, and ends with disposal or reuse of the toilet products. Implementation of a single component (e.g. a toilet facility) without adequate provisions for the other components of a sanitation system (e.g. collection, transfer and treatment) will just shift the problems from one point to another. It can even lead to accumulation of problems in such a way that the end result is even more detrimental to the objective of sanitation systems.

Toilet facilities are the first ring in the sanitation chain. The choice of a toilet facility is dependent on the physical characteristics of the environment within which it is going to be implemented; this means that the location profile should match the technical features of the facility. Moreover, this choice should fit into the social and institutional settings that are established in the place.

On the other hand, in decision-making to select a toilet facility, the next stages in the sanitation chain, i.e. collection, transfer, treatment and disposal or reuse, shall also be taken into consideration and the whole chain shall be selected. As certain toilet facilities can be combined with certain collection, transfer and treatment options, with choosing a toilet facility, the subsequent stages are also determined to some extent. The most common configurations of sanitation components in a sanitation chain are presented in Figure 1 to Figure 8. Brief description of different sanitation facilities are presented in Appendix I of this report.

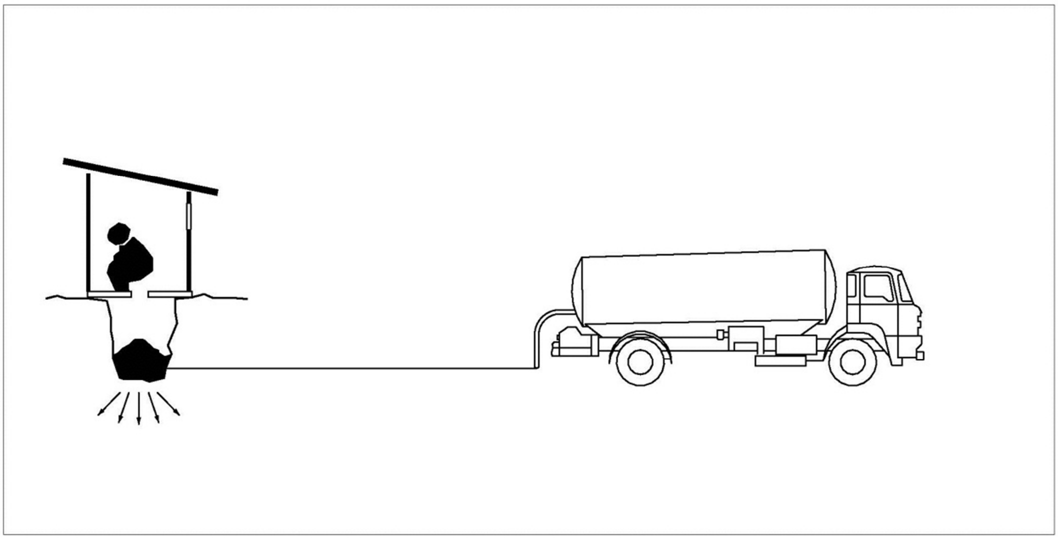


Figure 1: Dry toilet facility + soil infiltration of leachate (on-site treatment) + cartage of the faecal sludge

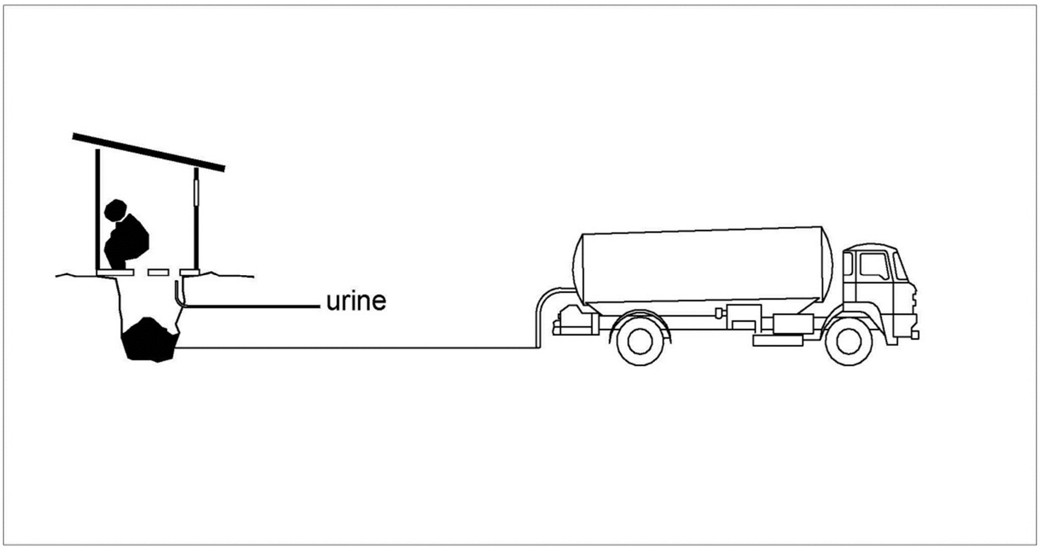


Figure 2: Urine diverting dry toilets + long retention of faeces (on-site treatment) + cartage of the faecal sludge (eco-san system)

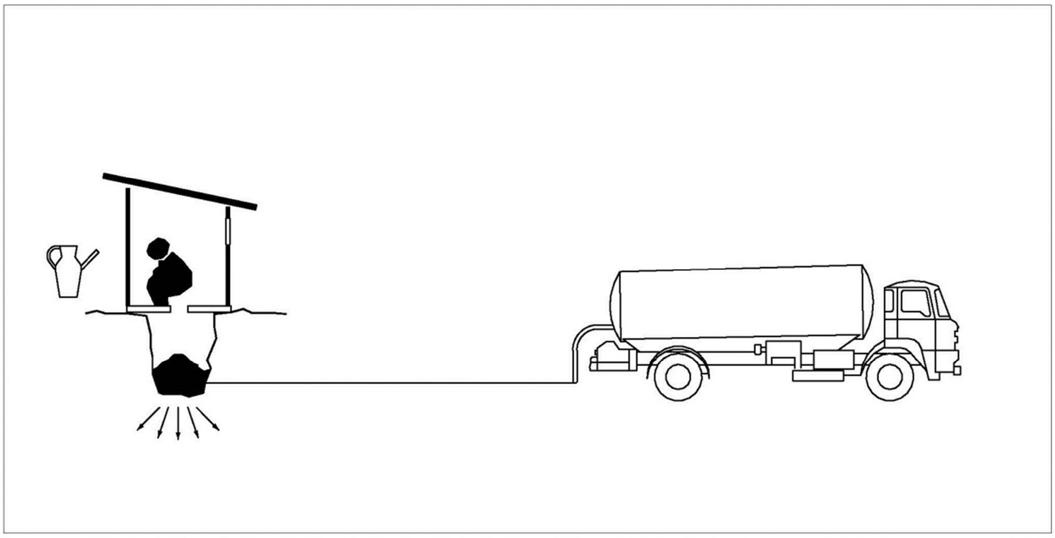


Figure 3: Pour-flush toilet (wet facility) + soil infiltration of leachate (on-site treatment) + cartage of faecal sludge

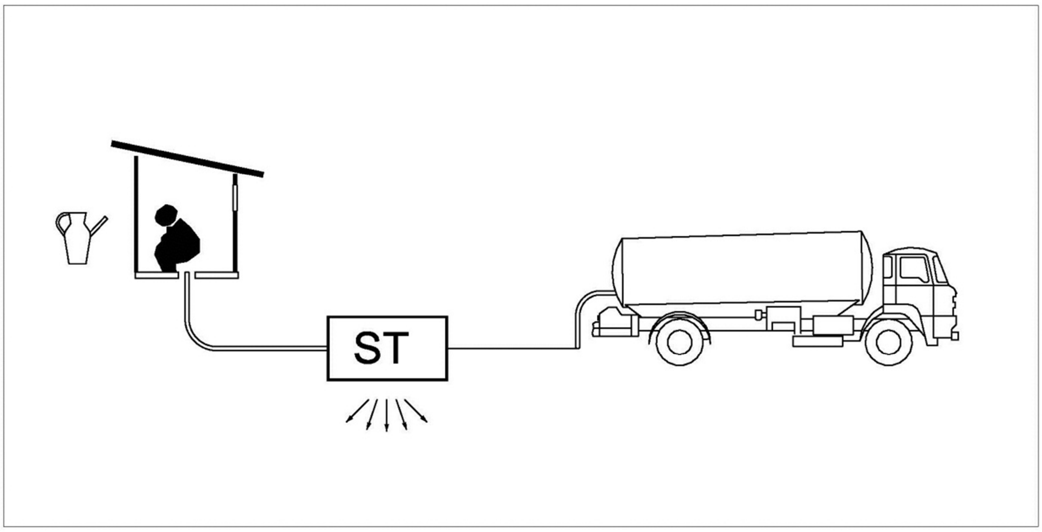


Figure 4: Pour-flush toilet (wet facility) + collection of sewage in septic tank + soil infiltration of the septic tank effluent (on-site treatment) + cartage of the faecal sludge

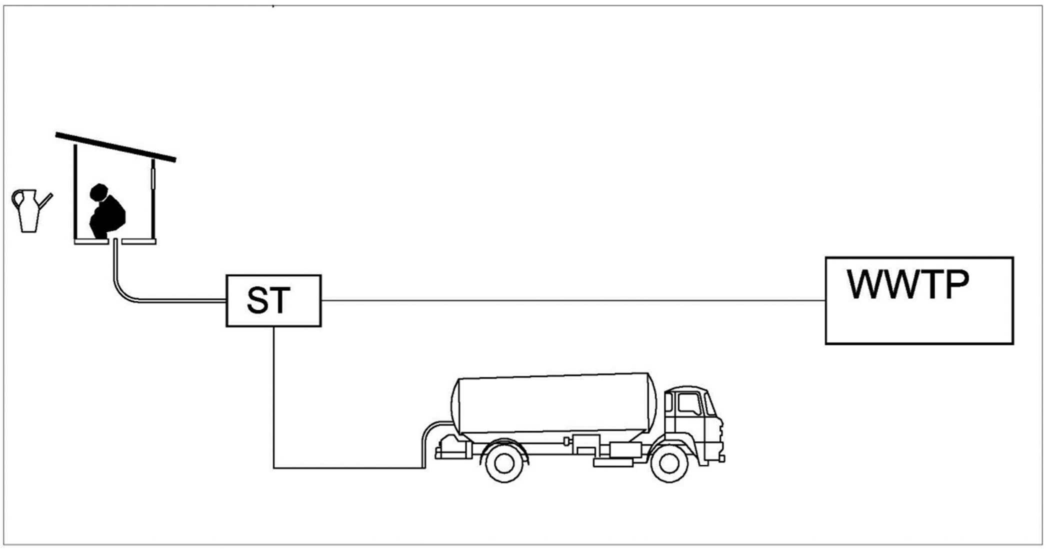


Figure 5: Pour-flush toilet (wet facility) + collection of sewage in a septic tank + transfer of sewage to a wastewater treatment plant with settled sewers + cartage of the faecal sludge from the septic tank

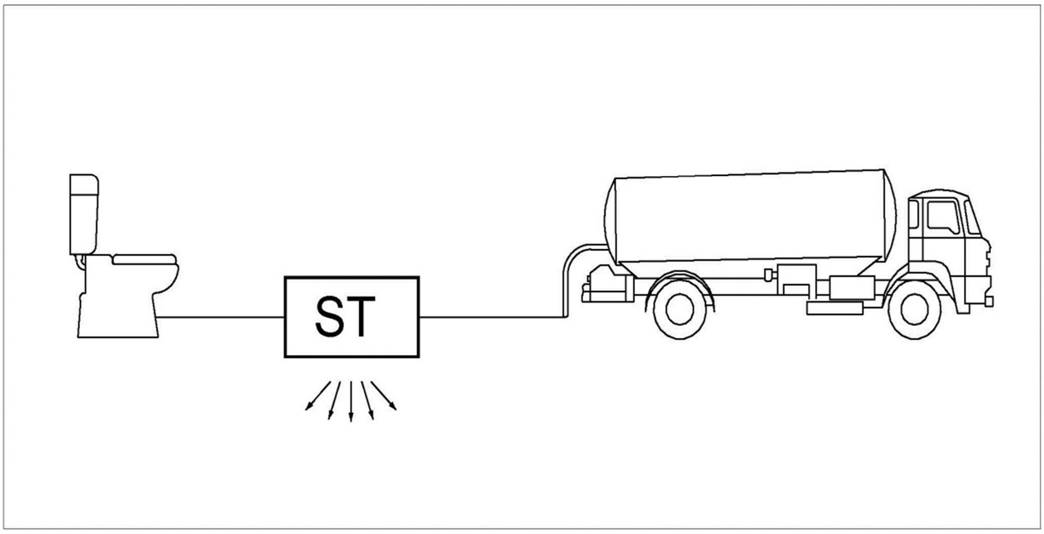


Figure 6: Cistern-flush toilet (wet facility) + collection of the sewage in septic tank + soil infiltration of the leachate from the septic tank (on-site treatment) + cartage of the faecal sludge

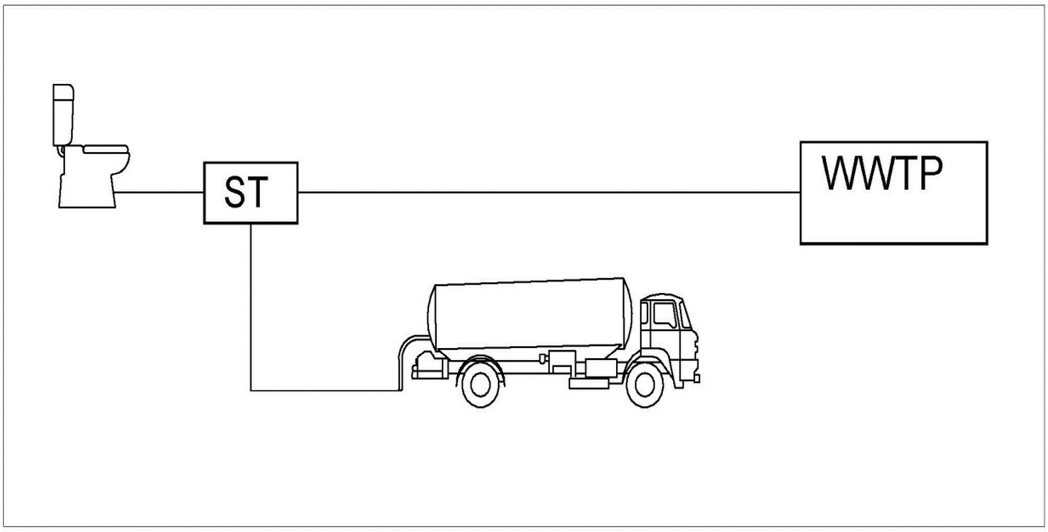


Figure 7: Cistern-flush toilet (wet facility) + collection of sewage in septic tank + transfer of sewage to a wastewater treatment plant with settled sewers + cartage of the faecal sludge from the septic tank

Figure 8: Cistern-flush toilet (wet facility) + collection and transfer of sewage to a wastewater treatment plant with sewer systems

The end products of sanitation chains may consist of faecal sludge, the effluent from wastewater treatment plants and urine from urine diverting facilities. The final products can be either disposed or reused. For faecal sludge the solutions may include (Brikké and Bredero, 2003):

- disposal to water; this solution is appropriate with regard to health risks if the faecal sludge has been retained for about 2 years (retention time to be determined by the temperature).
- disposal on land; this solution is appropriate with regard to health risks if the faecal sludge had been retained for about 2 years (depending on the temperature). However, if the land is not accessible by the public, lower retention times may be applicable too.
- reuse as fertilizer after composting, treating in waste stabilization ponds, anaerobic digestion process, sludge drying beds or any other sludge treatment facilities;
- discharge to wastewater treatment plants where it can be treated with the collected sewage.

For the wastewater treatment plant effluents the possible end may be:

- disposal to surface waters
- disposal to land (where it can be infiltrated)
- reuse in irrigation, industry or any other water demand nodes

Urine from urine diverting facilities may be used in agriculture to fertilize crops, due its high nutrient content.

It should be noted that in choosing a disposal or reuse method, the quality of the water or the sludge shall meet the minimum requirements for that specific disposal or reuse method as defined by local legislations. However, these legislations are also dynamic and prone to future changes.

3.2. Stage 1: Screening of sanitation options

To facilitate the evaluation of the sanitation options in the decision-making process, the number of options could be reduced by performing a screening stage in the beginning. In screening, some sanitation systems may be excluded from the options due to their essential requisites not being fulfilled by the existing situation. For instance, flush toilets have to necessarily work with water (essential requisite of the system is presence of water). So if water supply is not available in a place (existing situation does not fulfil the requisite of the system), flush toilets shall be eliminated from the options.

Therefore, the only criterion for screening is functionality. It should be identified if a specific facility can be implemented and will work under the existing situation, towards providing a certain level of protection against direct contact with human wastes. Otherwise, it will be excluded from the options without entering the evaluation stage.

For different sanitation types, the essential requisites for their functioning are presented in Table 2. If a sanitation facility fails to fulfil these minimum requirements, it will be eliminated from the options.

Based on the screening factors derived for different sanitation types, a screening flowchart is developed that can be used as a tool for filtering the implementable sanitation options from the non-implementable ones. This flowchart is a decision tree that asks users a series of questions. These questions are about the local situation in the place where the sanitation facility is going to be implemented, and point at the requisites of sanitation options as presented in Table 2. The answer Yes-No to the questions will determine if the essential requisites for a sanitation option are available or not. If not, the sanitation option will not function and therefore it should be excluded from the available options. The options that pass through the screening stage will enter the next stage, i.e. the probabilistic evaluation.

It should be emphasized that the screening flowchart as presented in this model does not lead to selection of a sanitation option, as it has been done in some of the previous decision-making support tools and is highly controversial as discussed in chapter 2; but rather leads to elimination of sanitation options that will not even work under the local conditions. Selection of a system is the result of the evaluation stage that comes afterwards.

Table 2: Essential requisites of different sanitation types. These requisites are the screening factors for sanitation options.

Sanitation Type	Essential Requisites
Wet sanitation facilities (e.g. flush toilets and their subsequent collection and transfer facilities: septic tanks, sewer systems)	Water supply availability
Sanitation facilities relying on soil infiltration of part of the waste material (e.g. latrines)	Soil type and groundwater table allowing infiltration to occur
Outdoor sanitation facilities (e.g. pit latrines)	Availability of an outdoor space for implementation of facilities
Ecological sanitation facilities	Availability of water absorbing material
	Provisions for users training
Facilities with bio-gas production	To be shared by a community to produce minimum usable amounts of bio-gas
Centralized facilities (e.g. centralized wastewater treatment plants, sewer systems)	Existence of a centralized institution for operation and maintenance of the system

The screening flowchart for sanitation options is presented below:

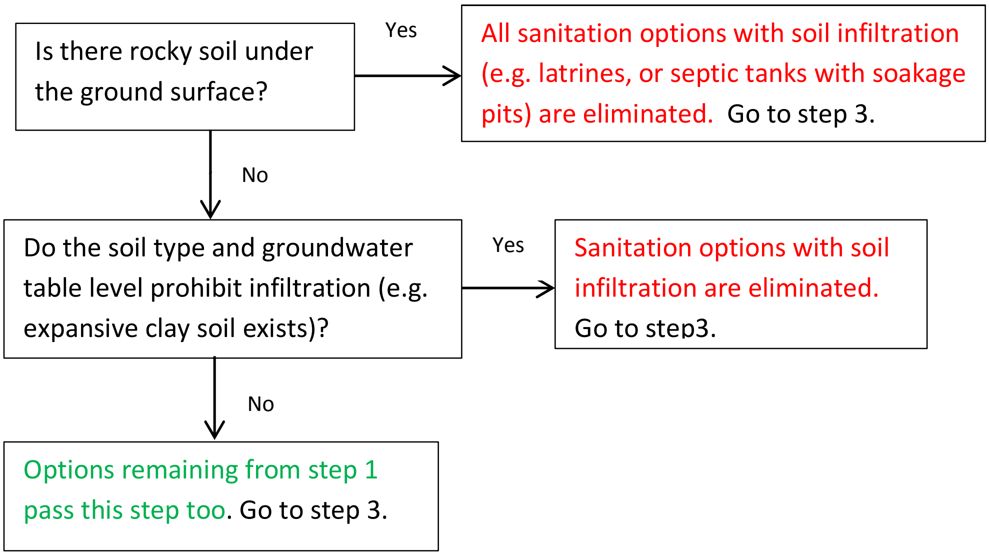
Step 1: For all sanitation options

Is water supply available?

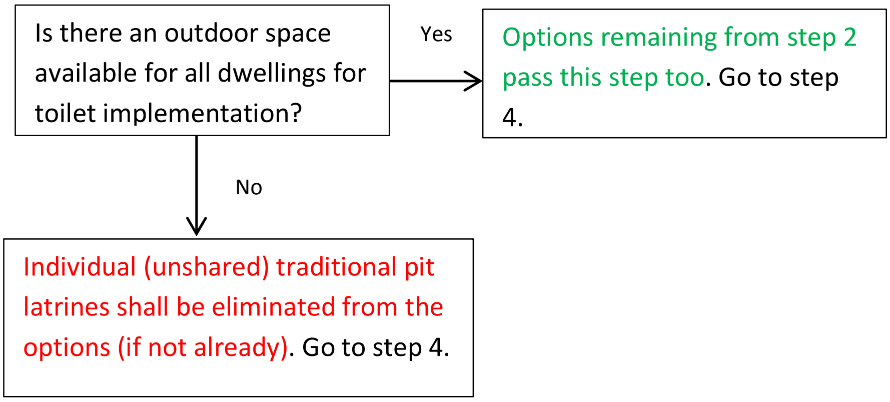
Yes → All sanitation options pass this step. Go to step 2.

No → Wet sanitation facilities (flush toilets and consequently septic tanks, sewer systems) are eliminated from the options. Go to step 2.

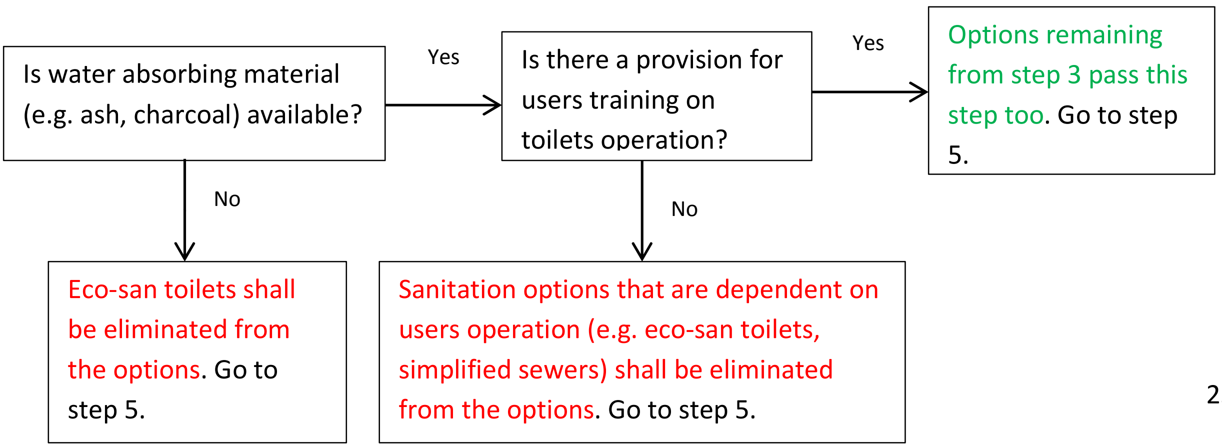
Step 2: For the remaining sanitation options from step 1



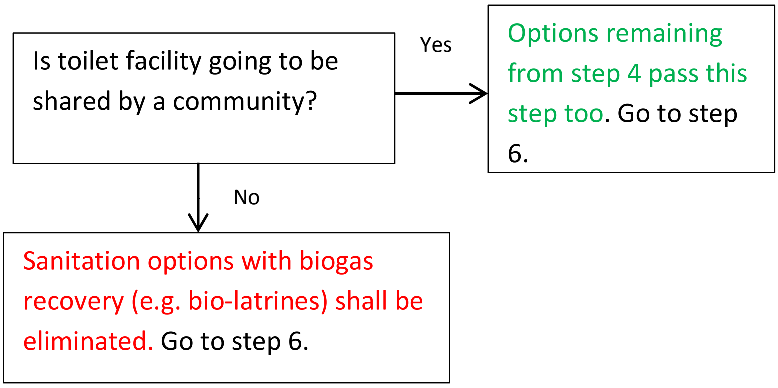
Step 3: For the remaining sanitation options from step 2



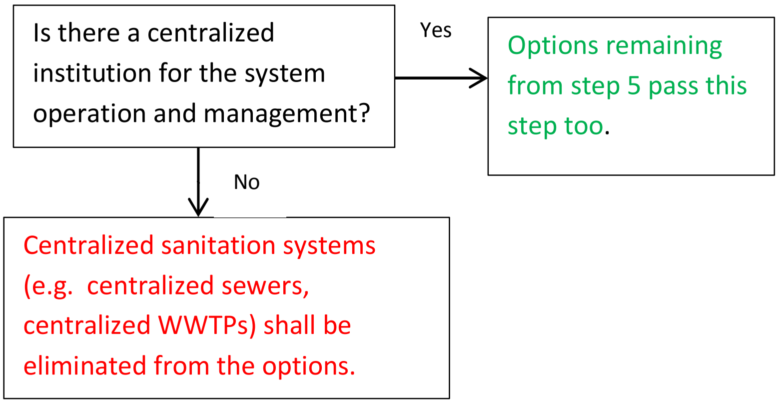
Step 4: For the remaining sanitation options from step 3



Step 5: For the remaining sanitation options from step 4



Step 6: For the remaining sanitation options from step 5



3.3. Stage 2: Probabilistic evaluation of sanitation options

The options that passed the screening stage (stage 1) will enter a comparative evaluation in which all remaining sanitation options that were not eliminated in the screening stage will be evaluated based on some criteria and their indicators. Each and every sanitation option will be evaluated with regard to those indicators. The final evaluation result for all options will be compared with each other for decision-making.

The criteria for comparative evaluation of sanitation systems in this work are the characteristics that are instrumental for fulfilling the objective of the system (i.e. providing some level of protection against direct contact with human wastes with an outlook for improvement of public health). They include: reducing exposure to health hazards, accessibility, reliability and sustainability.

The indicators for the evaluation criteria are presented in Table 3. To assess the facilities based on preventing exposure to health hazards the indicators include groundwater microbial pollution, exposure to faecal matter during usage of toilet facilities and exposure to faecal matter during waste collection. To assess the accessibility of facilities, the indicators are accessibility of the facilities for the users and accessibility of the reuse centres for the sanitation options that are made with provisions for energy and material recovery and reuse. For the reliability criterion, the indicators include reliability of water supply, reliability of users practices, reliability of system operation and maintenance management and the facilities proneness to flooding. With regard to the sustainability criterion, i.e. to assess if the system will continue its function as planned in the future as well, the indicators are compatibility of the system with future advances in water supply and compatibility of the system with the population growth.

Table 3: Criteria and their indicators for evaluation of sanitation options

Evaluation Criteria for Sanitation Options	Indicators
Exposure to Health Hazard	Groundwater microbial pollution (of concern where there is a local well for water supply)
	Exposure to faecal matter during use
	Exposure to faecal matter during waste collection
Accessibility	Accessibility for users (convenience)
	Accessibility of the reuse centres (only applicable to the facilities with direct reuse of on-site toilet products, e.g. eco-san, bio-latrine)
Reliability	Reliability of water supply
	Reliability of users practices (Users' acceptance)
	System maintainability
	Proneness to flooding
Sustainability	Compatibility of the system with population growth and prospective water supply coverage

The evaluation of the sanitation options is done in a probabilistic way, i.e. by assigning probabilities to certain outcomes occurring with regard to the defined criteria and their indicators. Through quantification of these probabilities (Chapters 4 to 7), it would be possible to assess the performance of the systems and their likelihood to bring about the desirable outcomes towards improving the public health.

The algorithm for the probabilistic evaluation of sanitation options is presented in Figure 9 and Figure 10. The input into this algorithm is a sanitation system type (e.g. one of the sanitation chains as illustrated in Figure 1 to Figure 8). There are evaluation nodes in which the system will be evaluated with regard to the indicators for each criterion as defined in Table 3. There are also some route planning nodes where it will be determined if a certain evaluation is at all necessary for the input sanitation type or not. For instance, if the sanitation type is not built outdoor, the evaluation for the indicator of *accessibility of users* is not necessary and this evaluation step can be skipped. The result node is where the result of a chain of evaluations can be aggregated for the final assessment. The aggregation may be done by multiplying the scores from different assessments for each criterion.

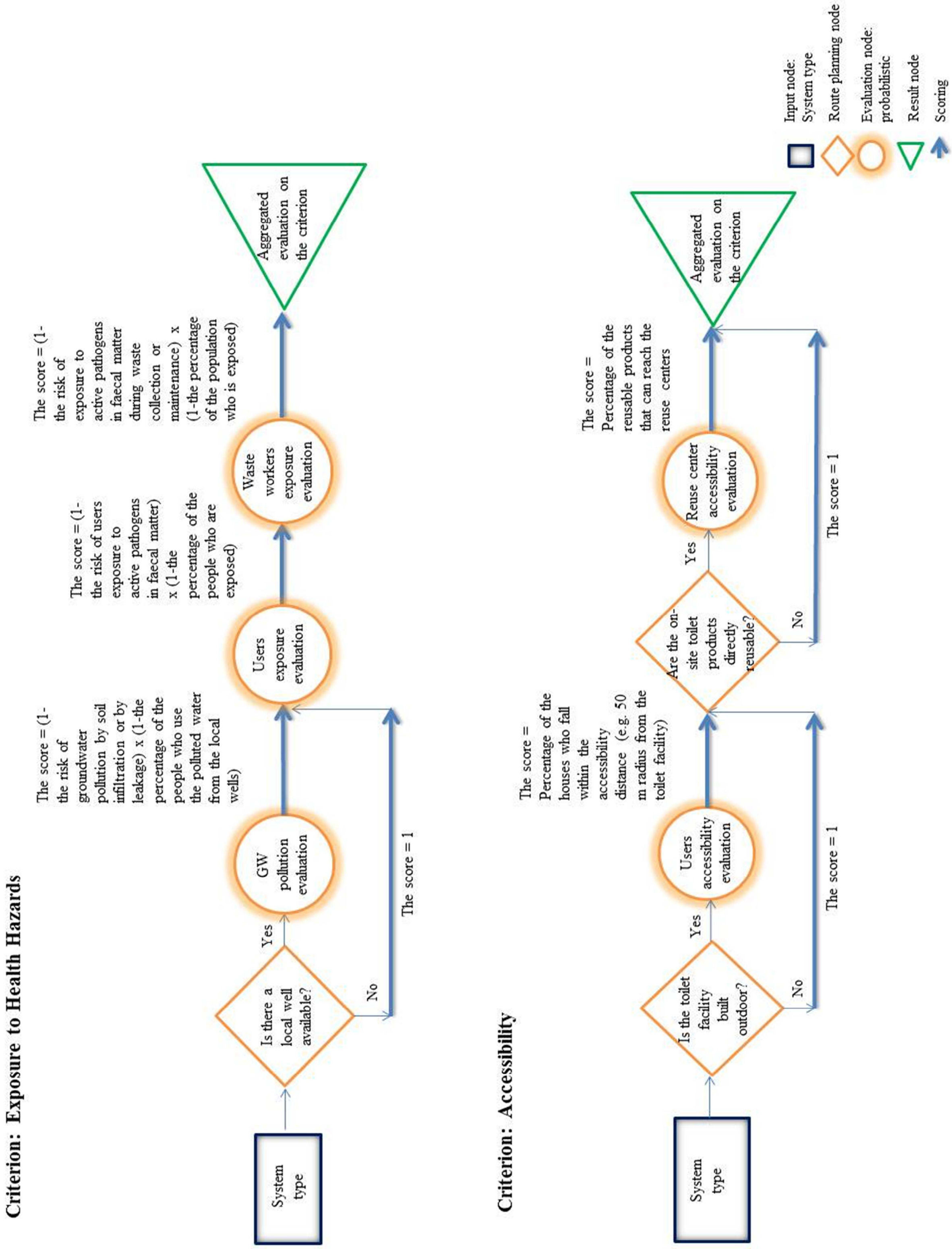


Figure 9: Evaluation algorithm of sanitation options with regard to exposure to health hazards and accessibility criteria

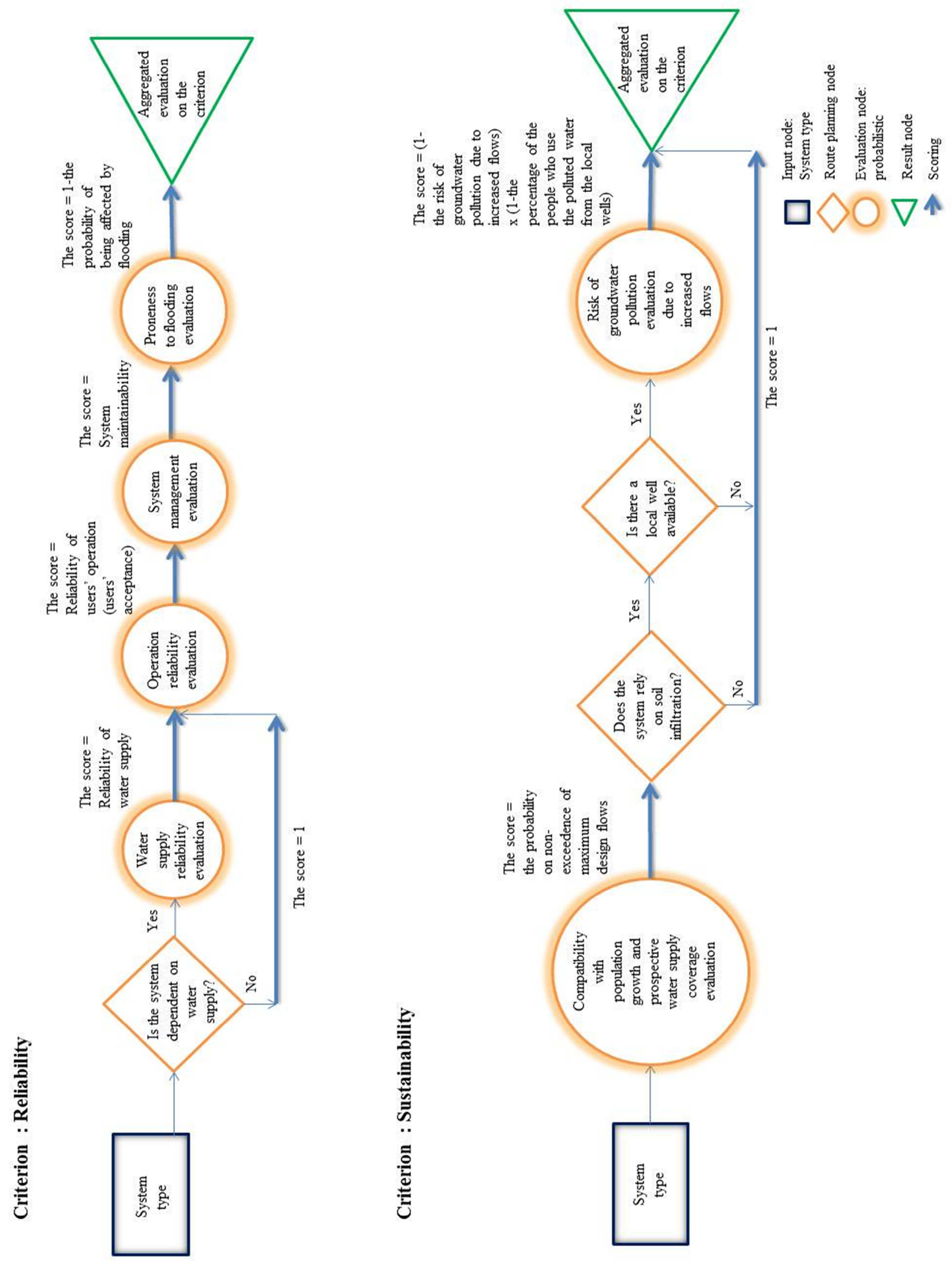


Figure 10: Evaluation algorithm of sanitation options with regard to reliability and sustainability criteria

4. Quantification of the Assessments for the Criterion: Exposure to Health Hazards

In order to quantitatively assess the sanitation options with regard to the indicators for the criterion of exposure to health hazards, some methods are developed in this thesis and presented in sections 4.1 to 4.3. Nonetheless, it is worth mentioning that these methods are not the only ways of quantifying the assessments. They are rather developed in order to show that, unlike the first impressions that one might get, it is not impossible to quantify such assessments; an impression that have been the major reason for turning into qualitative judgments by over simplifying the reality. Based on the available data and the extent of the details that the decision makers require for their judgment, other ways of quantifying the assessments may also be developed.

4.1. Groundwater microbial pollution

The microbial contamination of groundwater resulting from sanitation facilities is of concern if the water supply is from a local well and is not treated prior to consumption.

It is worth mentioning that microbial pollution is not the only concern, but nitrate contamination of groundwater resulting from sanitation facilities is also a point of concern in the long term. However, nitrate contamination of groundwater is not specifically addressed in this thesis.

Groundwater pollution may occur due to infiltration of leachate from the latrines into the soil or due to overflow and/or leakage from septic tanks and leakage from sewer pipes. However, once infiltrated into the soil the pathogens tend to attenuate due to various mechanisms such as: filtration, adsorption, biological predation and die-off, as the flow travels in the sub-surface. The degree of attenuation of pathogenic organisms in the sub-surface is dependent on the flow travel time from the pollution source to the well entrance, and is site-specific. Travel time is itself dependent on other factors including soil properties, thickness of the unsaturated zone, depth of the well, lateral distance between the well and pollution source, pump discharge rate, the areal recharge rate and the leachate loading rate.

In many cases, instead of using travel times, single-distance criteria between the sanitation facilities and the wells are used to ensure that the groundwater abstraction point is protected from pollution by sanitation facilities (Franceys et al., 1992; Howard et al., 2006). The weaknesses in using single distances in place of travel times were highlighted by Lewis et al. (cited in Howard et al., 2006) who noted that this distance may be overly conservative in some hydrogeological environments (thus limiting health gains from sanitation) and insufficient in other environments with rapid flow rates in the sub-surface. They suggested that these distances should be established based on local hydrogeological conditions (such as the water table depth and the nature of unsaturated zone) and the hydraulic load from the sanitation facilities (Howard et al., 2006).

A simplistic method for estimation of travel times in the sub-surface is presented in a British Geological Survey Commissioned Report: *Guidelines for assessing the risk to groundwater from on-site sanitation* (ARGOSS, 2001). This method estimate the travel time in the groundwater based on the soil type, pumping rate and the well screen depth in the format of some graphs. However, a more accurate way of estimating the travel time may be through ground water flow models. Such models range from a finite-difference model that can be built in excel, or an analytic element model that can be run in open-source programs such as W*h*AEM, to very complicated groundwater flow models. Estimation of travel time using the W*h*AEM geohydrological model is briefly explained in section 4.1.3.

Once the travel times from the pollution source to the well entrance are estimated, to quantify the probability of ground water pollution, 2 methods may be applied:

1- to use a Quantitative Microbial Risk Assessment (QMRA)
2- to quantify the semi-quantitative risk levels that are specified in some guidelines (e.g. ARGOSS) based on the travel times.

The first method could potentially be a more accurate way of quantifying the health risks caused by groundwater pollution, however it is data-intensive. The second method will provide an estimation of the risks; nevertheless, it is a practical solution for the situations where detailed site-specific data is not available. These methods are explained in sections 4.1.1 and 4.1.2.

4.1.1. Quantification of groundwater microbial pollution risk using quantitative microbial risk assessment

Quantitative Microbial Risk Assessment (QMRA) , as defined by Haas et al. (cited in Hamilton et al., 2007) is a four-step process:

a): Hazard identification (i.e. determining the pathogen of concern)

b): Exposure assessment (i.e. defining the exposure pathway which will result in estimating the concentration of the pathogen taken by the consumer)

c): Dose-response modelling (i.e. defining the infection probability as a function of the consumed dose)

d): Risk characterization (i.e. estimating the impact of the infection and/or illness caused by the pathogen of concern)

QMRA can be performed in 2 ways: the first is the deterministic QMRA in which the inputs and parameters are single values (point estimates). Deterministic modelling has the advantage of simplicity and has been used in several major water recycling guidelines such as: USEPA 2004, WHO 2006, Australian Guidelines for Water Recycling 2006 (Hamilton et al., 2007). The deterministic QMRA results in a single value for the probability of infection (or illness) from a specific pathogen. This value is then compared to the acceptable annual risk of infection (e.g. 1 in 10,000 people per year).

However, more recently, the stochastic QMRA has been developed in which point estimates have been replaced by probability distribution, which takes in to account the variation and uncertainty in the values (Hamilton et al., 2007), more specifically in the pathogen concentrations.

Stochastic QMRA can result in the frequency (or the probability) that the infection risk from a specific pathogen exceeds the acceptable infection risk. This could, potentially, be a very accurate way of quantifying the risks from groundwater pollution and would be desirable. However, the shortcoming lies in the lack of available data on pathogen concentration distributions in raw sewage and in stool and their being very much site-specific, i.e. dependent on the epidemiological status of the population in each location. Assuming that the pathogen of concern in QMRA for our case shall be a type of virus (due to their high infectivity and long survival in the environment compared to bacteria), the studies that have actually tested the virus concentrations in raw sewage have ended up reporting the mean values and the range of the values (e.g. Lodder and de Roda Husman, 2004 in the Netherlands; Feng et al., 2009 in US; Katayama et al., 2008 in Japan), but the actual individual concentrations are not presented in those studies. Even the mean values that are reported are very much different from place to place, indicating that using a generic value for evaluation may not be justified.

For developing countries (where the epidemiological situation of the population may be very different from those of developed countries) the data is even scarcer. One recent study in Kenya has only focused on detection of enteric viruses in raw sewage without determining the concentration values (Kiulia et al., 2010).

Without the detailed pathogens concentration data QMRA cannot be used as a method to estimate the risk of groundwater pollution from sanitation facilities.

4.1.2. Quantification of groundwater microbial pollution risk by quantifying the semi-quantitative risk levels presented in literature

Another method to quantify the groundwater pollution risk could be by quantifying the already existing semi-quantitative risk levels defined in literature for groundwater pollution. Howard et al. (2006) in a WHO document: *Protecting Groundwater for Health: Managing the Quality of Drinking-water Sources*, state that in developing countries some research has attempted to develop guidance on protection of groundwater against pollution from on-site sanitation without requiring detailed hydrogeological data. They refer to ARGOSS (2001) as an example and mention that its approach have been shown to be robust in water and sanitation planning and is effective in determining the risk levels based on local conditions where there is limited data available.

In ARGOSS, the risk of microbiological contamination is related to the potential for the pathogens to reach the groundwater supply. The risk is defined in terms of the travel time for the contaminant from the pollution source to the supply. Empirical evidence from a number of field studies has shown that a separation between the pollution source and the water supply equivalent to 25 days travel time is usually sufficient to reduce concentrations of faecal indicator bacteria to levels where detection within most samples is unlikely. However, the studies did not analyse for other pathogens such as viruses that are expected to survive for longer travel times in the subsurface (ARGOSS, 2001). Thus, in western Europe, where the aim is to deliver water with a quality to meet WHO standards (or national standards), a travel time of about 50 days have been set, which is based on attenuation of viruses from laboratory and field experiments (ARGOSS, 2001).

The values for travel time shall not be confused with survival time of pathogens in the soil or water, which is longer in most cases. During the flow travel time, attenuation processes such as filtration and adsorption work towards reduction of pathogens, which is independent of the natural survival time of pathogens. However, the value of 50 days travel time for groundwater protection have sometimes been controversial as there has been research which indicated that a lot longer travel times may be required to provide sufficient protection for groundwater wells (see Schijven and Hassanizadeh, 2002).

On the basis of travel time, three levels of risk have been defined in ARGOSS, i.e.:

- High risk: less than 25 days travel time
- Low risk: between 25 to 50 days travel time
- Very low risk: more than 50 days travel time

Using single travel times for risk analysis may not be fully protective, but their use is justified on the basis that they will provide protection against gross contamination and are a practical approach under the situation where detailed data is not available from the site (Howard et al., 2006).

The problem with the defined risk levels above is that they lack continuity and shift from one risk level to another. A travel time of 25.5 days may not be different from 25 days or 24.5 days considering the attenuation in sub-surface, however the risk level changes suddenly from high risk to low risk. If the problem of discontinuity in the risk levels is solved, it may be a practical method for estimating the risk of groundwater pollution when there is no detailed data available to perform the QMRA.

To overcome the discontinuity problem, a probability function can be assigned to the groundwater pollution versus the travel time. This function shall be exponential due to the fact that attenuation occurs faster in the upper layers of sub-surface (ARGOSS, 2001; Schijven and Hassanizadeh, 2002). High initial removal can be ascribed to special attachment sites that are present in the first few meters of soil passage but decrease rapidly with travel time or distance (Schijven and Hassanizadeh, 2002).

In this case, the probability of groundwater pollution vs. travel time has a shape similar to what is presented in Figure 11.

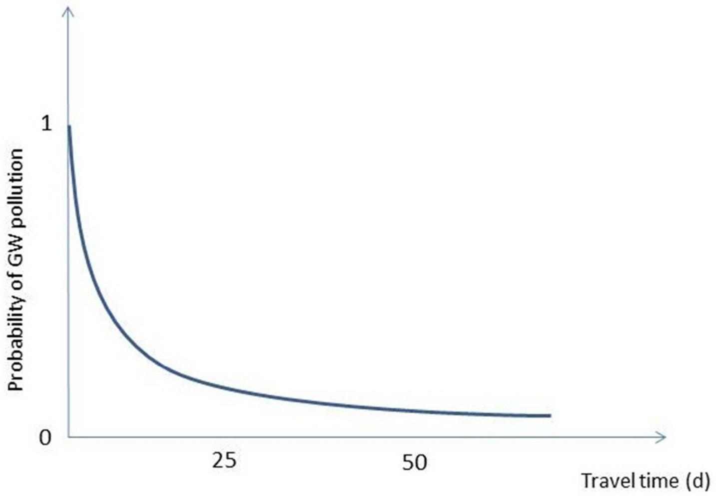


Figure 11: Groundwater microbial pollution risk curve as a function of flow travel time in the sub-surface. The numbers and the shape of the graph are roughly presented.

The exact shape of groundwater pollution risk versus the travel time is not known, nor is it known that the travel times of 25 or 50 days for instance relate to what exact value for the probability of groundwater pollution. However, it gives a coherent view on the risk levels that may exist. The aim of the sanitary engineers and decision makers in this regard shall be towards lowering the risk levels by influencing the shape of the graph (increasing the steepness) and increasing the travel times as far the available resources allow.

4.1.3. Estimation of the flow travel time in the sub-surface using W*h*AEM geohydrological model

The travel time of contaminated water from a pollution source (pit latrine or leaking sewer) to a well can be estimated using the ground water geohydrology computer program 'W*h*AEM'. W*h*AEM (Wellhead Analytic Element Model) is a public domain groundwater flow model originally designed to facilitate capture zone delineation area in support of the Wellhead Protection Programs and Source Water Assessment Planning for public water well supplies in the United States (Kraemer et al., 2007).

Geohydrological modelling for steady pumping wells, taking in to account the influence of hydrological boundaries such as rivers and recharge and also inhomogeneity zones is accomplished in W*h*AEM using the analytic element method.

When setting up a project in W*h*AEM, the binary base maps of the area in .bbm format can be used. A well or a well field can be defined with the relevant discharges and radius. Uniform flow can also be defined, knowing the head at one location. If there are more points with known heads, they can be used as test points to compare the modelled head with the observed (known) head. Aquifer characteristics can also be defined knowing some basic information including the base elevation, aquifer thickness, hydraulic conductivity and porosity. The recharge rate from the sanitation facility and the areal recharge are also the model input.

Once you run the model, the head contours will be drawn in the area and for a specified travel time, the capture zone will be displaced.

In Figure 12, an example well is modelled and it's capture zone is shown for a travel time of 25 days. W*h*AEM version 3.2.1 has been downloaded from the US Environmental Protection Agency (EPA) website (http://www.epa.gov/athens/software/whaem/index.html) and used in this example. The map used for this model is from an example map in Indiana, provided by EPA web server at http://www.epa.gov/ceampubl/gwater/whaem/us.html. The well discharge for this example is set at 500 m^3/d and its radius is 1.2 m. The aquifer is sandy type with a hydraulic conductivity of about 100 m/d, porosity of 0.2 and the thickness of 30 m. The recharge rate for this example is set at 0. The head contours in Figure 12 are also calculated by the program, given a known head at one location in the area. It should be noted that this example is just for indication of how the program works.

In Figure 13, the travel time has been changed to 50 days to indicate the change in the capture zone area. For this example, the sewage disposal point still doesn't fall in to the capture zone of 50 days travel time.

Using this modelling tool, the capture zones for having single or multiple wells, with or without inhomogeneity in the soil, with or without areal recharge, with or without the line sinks (rivers) can be calculated for different travel times.

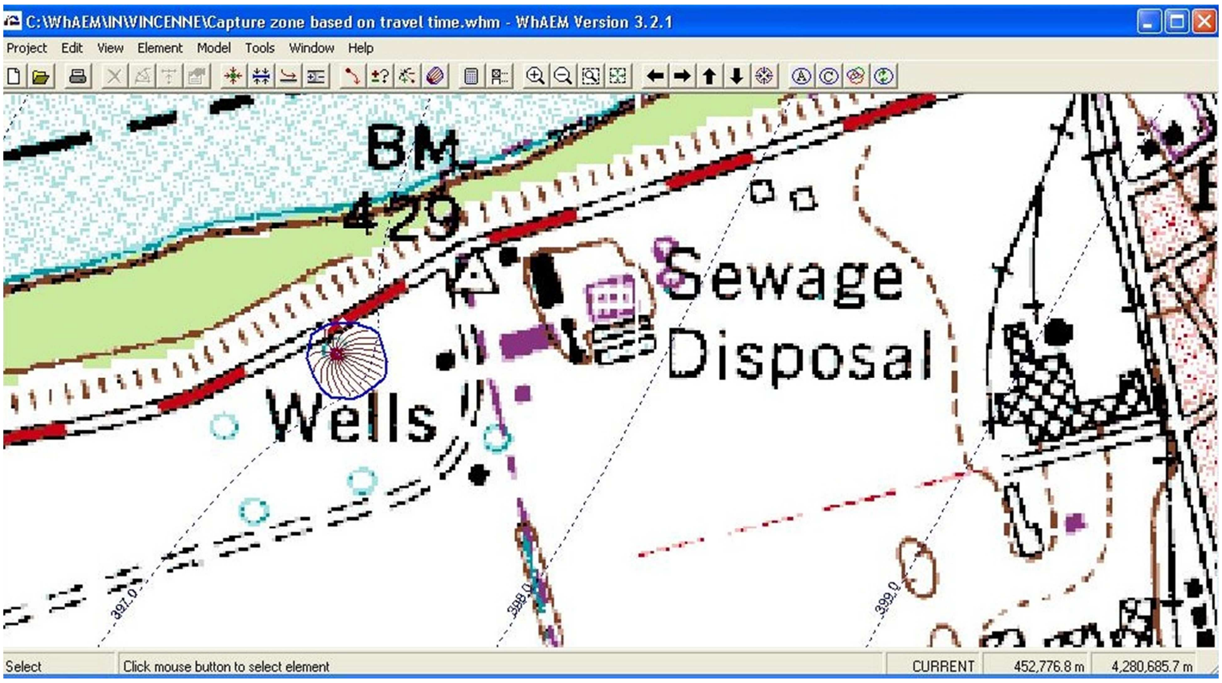


Figure 12: Capture zone for a sample well in uniform flow , travel time of 25 days, using WhAEM v.3.2.1. The well discharge is set at 500 m^3/d and its radius is 1.2 m. The aquifer is sandy type with a hydraulic conductivity of about 100 m/d, porosity of 0.2 and the thickness of 30 m. The recharge rate is set at 0.

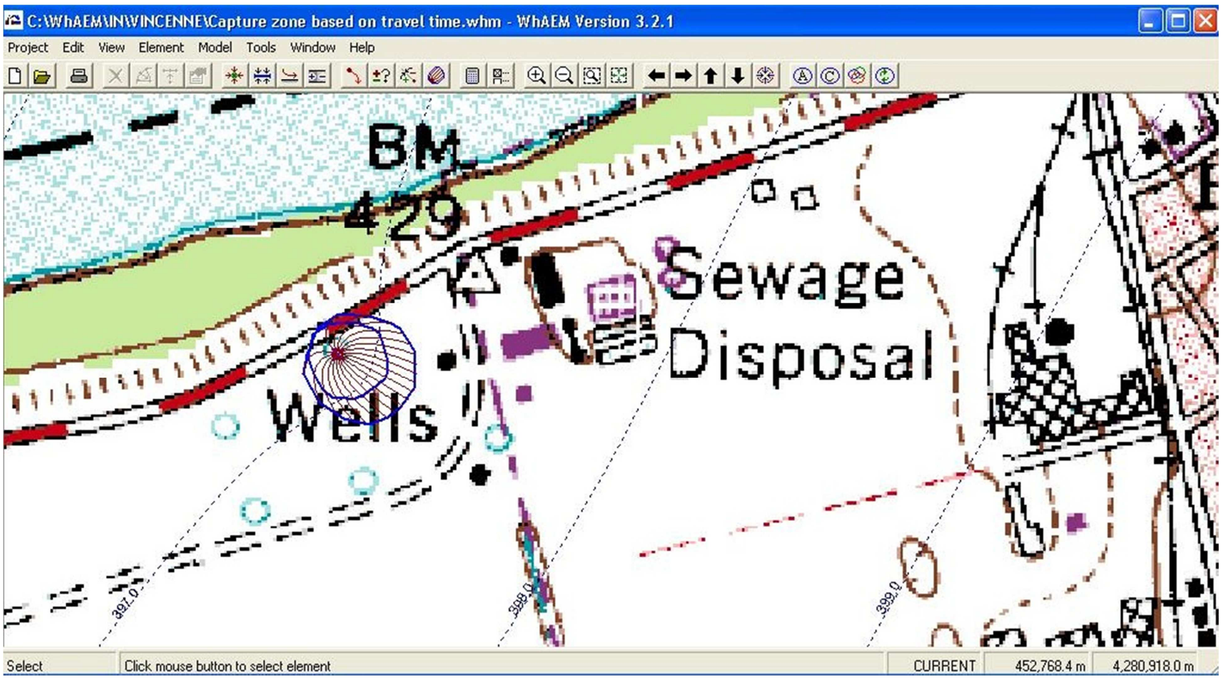


Figure 13: Capture zone for a sample well in uniform flow, travel time 50 days (big circle) vs. 25 days (small circle), using WhAEM v.3.2.1. The well discharge is set at 500 m3/d and its radius is 1.2 m. The aquifer is sandy type with a hydraulic conductivity of about 100 m/d, porosity of 0.2 and the thickness of 30 m. The recharge rate is set at 0.

4.1.4. Risk mitigation measures for groundwater microbial pollution from sanitation facilities

The measures that can be taken to lower the risk of groundwater pollution from sanitation facilities are the ones that can increase the steepness of the risk curve in Figure 11 and the ones that increase the travel times as far as possible.

From the sanitary engineering perspective, the risk mitigation measures that can be practiced include constructing artificial sand barriers (sand envelops) around the pit (Howard et al., 2006) that can reduce the flow velocity and increase the travel time. However, the economic feasibility of sand envelopes is questionable. Pickford (cited in Howard et al., 2006) commenting on recommendations for a 0.5 m sand envelope in India, states that this would cause four times increase in the volume of the excavation and a 1 m diameter increase for the pit. On the other hand, there is a requirement on replacement of these sand envelops every few years as the pore in the sand medium get blocked in time and inhibit the infiltration. This imposes extra maintenance load and costs to the system. Therefore the risk mitigation measures will be practiced to an extent that the available financial and institutional resources permit.

Another risk mitigation measures consist of deepening the well extraction point. This will also provide more travel time for the flow to reach the entrance of the well through which more attenuation may be achieved. Increasing the horizontal distance between the wells and the sanitation facilities is also another way of increasing the travel times.

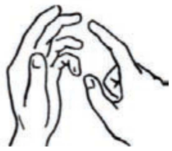
Dry latrines, compared to wet toilet facilities, impose lower hydraulic loading rates to the soil and the subsequent pollution risk will decrease accordingly (Howard et al., 2006). So a measure (that is not controlled by the sanitary engineers though) may include training of the toilet users to use less water for pour-flushing or shift to dry toilets completely.

Treating the extracted groundwater is also a way to reduce the health risks to the population arising from groundwater pollution from sanitation facilities.

4.2. Exposure of users to active pathogens in faecal matter

Exposure of users of sanitation facilities to active pathogens in faecal matter may occur through different pathways, including ingestion of excreta, dermal contact, contact with flies and mosquitoes and inhalation of aerosols or particles. These key pathways for different sanitation systems are described in Table 4.

Table 4: Key exposure pathways to faecal matter by users of sanitation facilities (After Stenström et al., 2011)

Exposure pathway	Illustration	Description of exposure	Relevant sanitation facility
Ingestion of excreta		Transfer of excreta to the mouth from the hands that were in contact with faecal matter or surfaces that were contaminated with faecal matter	All toilet facilities
Dermal contact		Entrance of pathogens through the skin (e.g. hook worms) via the feet or other exposed parts of the body	All toilet facilities with rough toilet floors (e.g. soil floors)
Contact with flies and mosquitoes		Transfer of excreta to the people or food via the flies or bites from disease carrying insects	Dry toilets and pour-flush toilets
Inhalation of aerosols and particles		Inhalation of particles or droplets carrying pathogens	Cistern-flush toilets

The risk arising from users exposure to active pathogens in faecal matter is composed of: the likely active pathogens dose at the exposure interface, the number of the people who would be exposed and the frequency of exposure (Stenström et al., 2011). These risk components are explained in sections 4.2.1 and 4.2.2 for 2 types of toilet facilities; dry toilets and flush toilets.

4.2.1. Health risk components in using dry toilet facilities

The exposure pathways to active pathogens in faecal matter for users of dry toilets consist of:

- ingestion of excreta because of touching the slabs or pedestals by hand and touching the mouth with hands, or falling in to the pits, especially by elderly people or kids or pregnant women,
- dermal contact that may transfer hookworms to the user,

- contact with flies and mosquitoes since they can breed on faecal matter (this exposure pathway is expected to be less significant in Ventilated Improved Pit latrines.).

The dose of the pathogens in exposure events is dependent on the exposure pathway and the epidemiological condition of the people who use a toilet facility.

The number of the people exposed is equal to the number of people who use the toilet facility. For unshared facilities, this will be equal to the number of the family members; while for shared facilities the number of users will be considerably larger.

The frequency of exposure is daily and could be equal to the number of the toilet visits per day (about 5 times). The contact time in each toilet visit could be less than or equal to the duration of toilet visit.

4.2.2. Health risk components in using wet toilet facilities

The exposure pathways to active pathogens in faecal matter for users of flush toilets consist of:

- ingestion of excreta because of touching different toilet surfaces by hand and touching the mouth with hands,
- dermal contact that may transfer hookworms to the user,
- for pour-flush toilets, contact with flies and mosquitoes if water for pour-flushing is kept in open vessels where the insects can breed,
- for cistern-flush toilets, inhalation of aerosols that rise from cistern flushing.

The dose of the pathogens in exposure events is dependent on the exposure pathway and the epidemiological status of the people who use a toilet facility.

The number of the people exposed is equal to the number of people who use the toilet facility. For unshared facilities, this will be equal to the number of the family members; while for shared facilities the number of users will be considerably larger.

The frequency of exposure is daily and could be equal to the number of the toilet visits per day (about 5 times). The contact time in each toilet visit could be less than or equal to the duration of toilet visit.

4.2.3. Quantification of exposure risk for users of different toilet facilities

Although the components of the disease risk that might arise from the users exposure to active pathogens during their toilet visits are known, systematic studies on these factors and the disease outcome is lacking (Stenström et al., 2011). Many studies have reported the results of interventions in sanitation and water supply to reduce illness in developing countries. As an example, a study in Brazil reports a 26% reduction in the prevalence of diarrhoea after execution of a large sanitation program (Barreto et al. cited in Ferrer et al., 2008). However the results from such studies are not always coherent and sometimes even contradicting. For instance, a study in per-urban communities in Nigeria indicates that while improved water supply and sanitation facilities may reduce the prevalence of ascariasis, the morbidity problems linger, with infection intensity being unexpectedly higher among the ones who had access to improved sanitation (Asaolu et al., 2002). Similar results on failure of improved water supply and sanitation to combat disease infection are also reported from Bangladesh, Lesotho and Guatemala (Asaolu et al., 2002).

Shuval et al. (cited in Asaolu et al., 2002) suggest that these variations in results show that the outcome of such interventions is largely dependent on the coverage and the general socio-economic conditions of the society. A more recent study by Ferrer et al. (2008) confirms this idea. They identified more than 30 factors associated with diarrhoea occurrence, and grouped them into socioeconomic factors, environmental factors (water and sanitation), person-to-person contact factors and factors associated with food contamination. They investigated the contribution of each factor to the diarrhoea occurrence among children in the city of Salvador in Brazil. The results indicated that socioeconomic factors contributed the most to diarrhoea occurrence, followed by inter-personal contacts.

While intuitive judgement (as used in some decision-making approaches for sanitation systems) may incline towards assigning a higher disease risk to the users of dry toilets compared to flush toilets, the real available information does not support that. In fact no study could be found (up to the date of this report) in which disease risk from different types of toilet facilities were compared systematically; but the comparison has rather been between the groups who had access to some kind of toilet facility and those who had no toilet facility. Fewtrell et al. (2005) did a meta-analysis on comparing the evidence of the effectiveness of sanitation (and water supply and hygiene) interventions to reduce diarrhoea, screening 2120 publications. They found 4 studies on the effect of sanitation interventions on health. Only 2 of them had data that could be used in meta-analysis: one investigates the impact of flush-toilets (compared with no toilet facility) in Cholera incidence in Philippines (Azurin and Alvero, 1974), and one investigates the impact of latrine installation on diarrhoea morbidity in Lesotho (Daniels et al., 1990). The summary meta-analysis suggests that sanitation interventions reduce illness with a pooled relative risk of 0.68 (Fewtrell et al., 2005).

Therefore, since the comparative evaluation in the decision-making process is among different types of toilet facilities that are all considered as improved sanitation (against open defecation), the risk associated with users exposure to pathogens in faecal matter can be assumed the same for different facilities. This is also in line with the approach of Stenström et al. (2011) in their book : *Microbial Exposure and Health Assessment in Sanitation Technologies and Systems*, where they assign an equal risk level to users of different toilet facilities.

If further studies in the future focus on comparing different toilet facilities in this regard, this risk level can be revised according to the relevant results.

4.2.4. Risk mitigation measures for users of toilet facilities

Although the exact health risks resulting from the toilet use are not known, the engineers and planners shall aim at reducing the exposure risk to active pathogen for the users of toilet facilities. This can be achieved via different practices that reduce the exposure to pathogens and thereby reduce the disease risk arising from that.

From the sanitary engineering perspective, the risk mitigation measure that can be practiced is related to the appropriate construction of the toilet facilities according to the design standards that facilitate functioning of the facility according to its defined goal. For instance, VIP latrines that have a vent pipe designed and built according to the design standards, will result in less flies being attracted to the toilet room compared to the traditional pit latrines; or as another example, in communal flush toilet facilities where the hygienic conditions are not assured, building squatting pedestals may be more appropriate compared to sitting arrangements (Stenström et al., 2011). The design guidelines for different types of toilet facilities can be found in literature, including a WHO document, *A Guide to the Development of on-Site Sanitation* by Franceys et al. (1992).

There are other measures that are not controlled by the sanitary engineers but can be recommended to the users, facility managers and operators. Toilet facilities that are kept clean have significant lower risk level for the users (Stenström et al., 2011). For squatting toilets, the slab hole shall be big enough to avoid defecation on the slab, and shall be small enough to avoid falling of the users. The toilet floor shall be smooth to ensure better cleaning.

For pour-flush toilets, using rain water would impose less health risks to the users compared to using grey water (Stenström et al., 2011). The water should be stored in a separate storage tank. Bulky anal cleaning material that can clog the U-trap (e.g. corncobs) should not be used.

Covering the lid of the cistern-flush toilets before flushing is also a way of reducing the risks caused by the aerosols and particles.

Training of the toilet users to practice hand washing after toilet visit is also another way of reducing the health risks associated with toilet use, if there is water available for hand washing.

4.3. Exposure of sanitation workers to active pathogens in faecal matter

Emptying of faecal sludge from the latrines or septic tanks and maintenance of sewer systems exposes health risks to the workers resulting from their contact with the active pathogens in the excreta. The risk components consist of: the concentration of the active pathogens at the exposure interface (which is dependent on the exposure pathway, the epidemiological status of the users and the degree of treatment that has been achieved in the system prior to the contact event), the number of the people exposed, the frequency of exposure and the contact time.

The risk components may vary for different emptying or maintenance practices, as explained in sections 4.3.1 to 4.3.3.

It is worth-mentioning that the health risks for sanitation workers is not only associated with pathogens. A study on sewage network workers in Egypt (Farahat and Kishk, 2010) reveals significant higher frequencies of cognitive impairment among them compared to the control group, due to exposure to H_2S gas. H_2S is produced through decomposition of organic matter by bacteria and exposure of sewer workers is not limited to fatal concentrations, but lower dose exposure is encountered during routine work of inspection and maintenance of sewer networks (Farahat and Kishk, 2010).

4.3.1. Exposure of workers to active pathogens during manual emptying of faecal sludge from on-site sanitation

The exposure pathways to faecal matter during manual emptying of faecal sludge from on-site sanitation facilities consist of (after Stenström et al., 2011):

- ingestion of excreta that may occur through secondary oral transmission via hands or even accidental direct ingestion,
- dermal contact that may transfer hookworms to the user,
- contact with flies and mosquitoes since they can breed on faecal matter,
- inhalation of particles that rise in the air during the emptying practice.

The dose of the pathogens in exposure events is dependent on the exposure pathway, the epidemiological status of the people who share a toilet facility and the degree of pathogen removal that has been achieved before the emptying practice. In areas where the temperature reaches up to 20°C, a total storage time of about 1.5 to 2 years will eliminate most bacterial pathogens and will substantially reduce viruses and protozoa and parasites (Winblad and Simpson-Hébert, 2004). Higher temperatures reduce this attenuation time. However, if single pits and tanks are used, they always contain fresh excreta that were not stored long enough for the attenuation to be achieved. In contrast, double pits in which the content of the first pit has been stored for a few years before emptying, impose no or very little health risk to the people who come into contact with that.

The number of the people exposed is equal to the number of workers (for each event about 1-5 people) and the people in the surrounding community who come into contact with the spills from the emptying practice.

The frequency of exposure is high for the workers who do scavenging as their job. The potential contact time in each practice will be in the order of 1 to a few hours.

4.3.2. Exposure of workers to active pathogens during motorized mechanical emptying of faecal sludge from on-site sanitation

Although it may seem that motorized emptying of faecal sludge prevents workers contact with faecal matter, but the operation consists of several manual tasks such as opening and closing the collection chambers and connecting the hose and the pumps (Stenström et al., 2011). Moreover, the sludge may suddenly be sprayed on the operator and on the surrounding area (Stenström et al., 2011).

The exposure pathways to faecal matter during motorized emptying of faecal sludge from on-site sanitation consist of:

- ingestion of excreta may occur through secondary oral transmission via hands or even accidental direct ingestion
- contact with flies and mosquitoes since they can breed on faecal matter
- inhalation of particles that rise in the air due to sudden spray of the sludge

The dose of the pathogens in exposure events is dependent on the exposure pathway, the epidemiological status of the people who share a facility and the degree of pathogen removal that has been achieved before the emptying practice.

The number of the people exposed is equal to the number of workers (for each event about 1-5 people) and the people in the surrounding community who come into contact with the spills from the emptying practice.

The frequency of exposure is high for the workers. The potential contact time in each exposure is short, in the order of a few seconds or minutes, however the total contact time (resulting from the high frequency) may not be short.

4.3.3. Exposure of workers to active pathogens during maintenance of sewer systems

The people who do the maintenance on the sewer systems (conventional, simplified or settled sewers) are exposed to faecal matter and in danger of health impacts resulting from that.

The exposure pathways to faecal matter consist of:

- ingestion of excreta may occur through secondary oral transmission via hands or even accidental direct ingestion
- inhalation of particles that may rise in the air during the maintenance practice

The number of the people exposed is equal to the number of workers (for each event about 1-5 people) and the people in the surrounding community who come into contact with the spills from the maintenance practice.

The frequency of exposure is high for the workers and is low for the surrounding community, as maintenance events at the same location are not likely to happen frequently. The potential contact time in each exposure is in the order of a few minutes to few hours; however the total contact time (resulting from the high frequency) will not be short.

4.3.4. Quantification of the exposure risk for sanitation workers

To quantify the health risks resulting from emptying faecal sludge or maintenance of sewer systems, it can be assumed that the health risks grow almost linearly with the total contact time, considering that the quality of the faecal sludge is constant. For a certain pathogen concentration, the more frequently the exposure occurs and the longer it takes in each event, the greater the resulting health risk would be. After a certain contact time, the risk reaches its maximum level and remains constant. This behaviour is validated using an arbitrary dose-response equation and calculating the probabilities of infection from different contact times using an arbitrary pathogen concentration in the faecal sludge. In Figure 14 an exponential dose-response equation has been used to calculate the probability of infection for different contact times. The dose in the dose-response model consists of the contact time multiplied by the concentration of the active pathogens in the faecal matter. As the concentration of pathogens is constant, the probability of infection changes with changing contact time.

The impact of different pathogen concentrations in the faecal matter on the probability of infection may be tested by choosing a lower concentration and observing the changes in the probability of infection versus the contact time. The blue line in Figure 14 is drawn for the case where the concentration of active pathogens in faecal matter is lower compared to the green line. In other words, for each contact time the green line is associated with the higher dose compared to the blue line, which is due to the lower degree of treatment (shorter storage time prior to emptying for instance) that has been achieved in the faecal sludge. Nevertheless, again after a certain contact time (which is longer for lower concentration; see the blue curve), the risk reaches the maximum level again. This is because the dose consists of both the concentration and the contact time and while the concentration has decreased, larger contact times will compensate for that and raise the risk to the maximum level again.

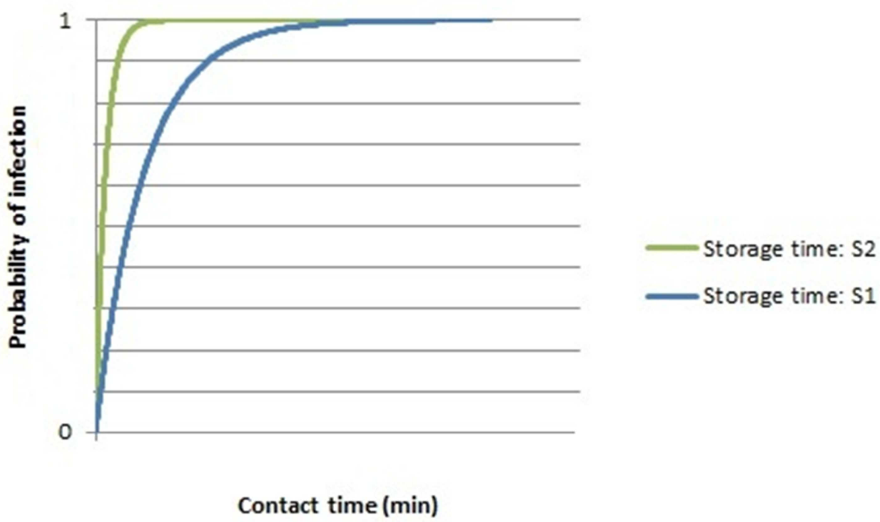


Figure 14: An example health risk vs. contact time graph for the workers during emptying or maintenance practices of sanitation facilities. The green line indicates a situation where the storage time of the faecal sludge (S2) prior to exposure events has been shorter compared to the storage time for the blue line(S1): S1>S2.

As it can be concluded from the graphs in Figure 14, for the common contact times that may occur in practice, the risk increases almost linearly with time. The exact slope of the risk curves is dependent on the pathogen type and its related dose-response model, and also the pathogen concentrations that has remained in the faecal matter. In practice this may not be known for every situation. However, some estimations already exist:

- In warm climate regions (temperature above 20°C), if double pits are used, after 2 years of storage time for the first pit the curve will have a very small slope as the concentration of pathogens is negligible.
- In comparison of dry pits and wet pits and septic tanks, with equal storage time, the dry pits will possess a less steep curve as the inactivation of pathogens occurs faster in dry environments (Franceys et al., 1992).
- In case of a disease outbreak, the slope of the curves increases.

As mentioned in sections 4.3.1 to 4.3.3, the total contact time (i.e. the frequency of the practices multiplied by the contact time in each practice) for the sanitation workers is not short for any of the sanitation systems with different emptying or maintenance methods. Therefore, for a specific pathogen concentration in the faecal sludge and without any protective measures for the workers, the health risks arising from different emptying or maintenance practices may not be considerably different. In other words, manual emptying for instance, may result in a relatively longer contact time in each exposure event but not necessarily a very higher risk compared to motorized emptying as the total contact time for the workers (resulting from the high frequency of their exposure) may be high enough to pass the steep part of the graphs as in Figure 14. This is in line with the approach of Stenström et al. (2011) who also assign a 'high risk level' to the workers in different kinds of emptying or maintenance practices. Therefore, what can make the big difference in the risk levels is through lowering the risk curves as indicated in Figure 14.

The conclusion that can be derived for planners and decision makers is that without any risk mitigation measures, there is a significant health risk that can be imposed to the workers during emptying or maintenance, whatsoever the sanitation facility. Reducing this risk is only possible through some measures that lower the risk curves (decrease their steepness) and through reducing the contact time of the workers with the faecal matter by means of protective measures.

4.3.5. Risk mitigation measures for sanitation workers

Although the exact risks of workers exposure to faecal matter is not known, it is known that the risk is a function of the contact time and is dependent on the treatment level that has been achieved prior to the contact event.

From the sanitary engineering perspective, the possible measures include the ones that facilitate longer storage time and higher pathogen removal prior to exposure events (i.e. reducing the slope of the risk curve). When enough land is available, double pits shall be constructed.

For sewer lines, the design and construction shall be done in a way that blockage and cracks are avoided and the pipes shall be laid deep enough to avoid physical damage from the surrounding environment. This will lower the maintenance frequency and therefore the possible exposure frequency.

Other measures that can be practiced by the managers and planners include training of the workers with regard to the health risks that entail in their job and providing them with the equipment that reduces the contact with the faecal matter (e.g. long handled shovels, long suction hoses). Personal protection equipment such as boots, gloves, clothing that covers the whole body and face masks are essential in manual practices (Stenström et al., 2011). Washing and if possible disinfection facilities shall also be provided for the workers.

5. Quantification of the Assessments for the Criterion: Accessibility

In order to quantitatively assess the sanitation options with regard to the indicators for the criterion of accessibility, some methods are developed in this thesis and presented in sections 5.1 to 5.2. These methods are rather developed in order to show that, unlike the first impressions that one might get, it is not impossible to quantify such assessments; an impression that have been the major reason for turning into qualitative judgments by over simplifying the reality.

5.1. Users' accessibility to toilet facilities

Accessibility of the toilet facilities for the users is concerned in situations where these facilities are built outdoors. Indoor toilet facilities are obviously preferable with regard to accessibility criteria, however the toilet type and the available resources may not allow this to happen. Dry toilets and pour-flush toilets that rely on direct soil infiltration would need to be built outdoors. This already reduces the accessibility of the facilities in comparison with flush toilets that can be built inside the buildings. In these cases it is still preferable that the facility is built within the dwelling (in the yard for instance). However if a dwelling does not own the required space for the toilet facility, the facility will be located outside the house and preferably as close as possible to the house.

In highly congested urban areas, if outdoor toilet facilities are used (e.g. latrines), it may not be possible for every family to have a private facility outside their dwelling due to lack of space. In this situation shared toilets shall be constructed. In this case the accessibility criteria can become a concern because not all the users will have equal access to the facilities.

Lack of toilet facilities inside or next to the home can impose physical security risk to women and children who need to use the facilities, especially during the nights. Studies have also shown that children, and in particular girls, are not willing to attend school if there is no toilet facility available (COHRE et al., 2007).

A sanitation facility being located distant from the house can also cause severe accessibility problems for the elderly people and the disabled ones.

5.1.1. Quantification of users' accessibility to toilet facilities

The definition of accessibility shall be determined by the decision makers, however some guidelines such as the UN published *Manual on the Right to Water and Sanitation* (COHRE et al., 2007) refer to a 50 m distance to the sanitation facility as the accessibility indicator. However, distance alone may not be enough to define the accessibility of sanitation facilities, but the time that the users should spend to use the facility matters. This time, consists of the time the users shall spend on the way (for which the distance is the indicator) and the waiting time at the facility. The latter can be represented by the number of the people among whom the facility is shared. *The Manual of the Right to Water and Sanitation* refers to a number of maximum 20 people who may share the toilet facility (COHRE et al., 2007). This determines the number of the facilities to be built, regardless of the sanitation type that is going to be selected.

Once the maximum accessible distance is determined (e.g. 50 m) and the location of the toilet facilities is specified, the number of the houses located within that distance will be calculated for the underserved area. The ratio of the number of the houses within the acceptable distance to the total number of the houses that are served by the facility will indicate the accessibility ratio. This ratio can then be the quantified value for the evaluation of different options with regard to the accessibility criterion.

The areal map of an example area in Kisumu, Kenya is shown in Figure 15. This area is relatively congested. The red spots show the possible locations of the toilet facilities. The white circles cover the areas with less than 25 m distance from the toilet facilities. The orange circles covers the areas with 50 m distance and the yellow circles cover the areas within 75 m distance to the toilet facility.

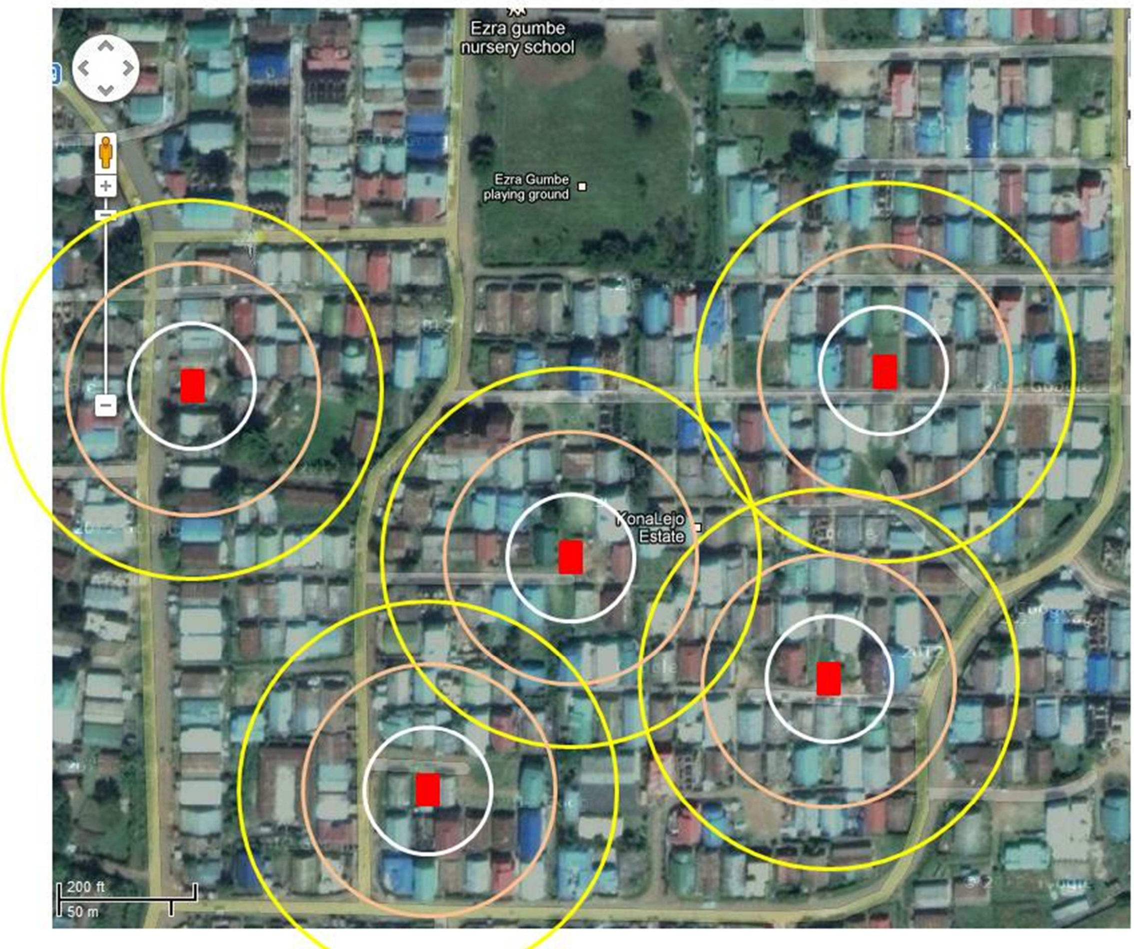


Figure 15: The areal map of an arbitrary congested area in Kisumu, Kenya. The toilet facilities are shown by red spots. The white circle represents the coverage area of 25 m distance, the orange circle covers 50 m distance and the yellow circle covers areas with 75 m distance

The number of the houses that fall into each of the circles is counted. The portion of the houses within each distance radius compared to the total number of the houses in the area can also be calculated (see Table 5). The cumulative graph for the number of the houses vs. the distance to the toilet facility and the cumulative graph for the portion of the houses with at least distances to the toilet facility can also be drawn (see Figure 16).

From these graphs the portion of the houses with a defined accessible distance (e.g. 50 m) can be derived (0.31 for this example). This ratio can then be used to assess the toilet facility with regard to the accessibility criteria.

Table 5: Number of the houses within a certain distance to the toilet facilities; an example case in Kisumu, Kenya

Distance of the house to the toilet facility (m)	**25**	**50**	**75**	**200**
Cumulative number of the houses with at least distance to the toilet facility	42	139	295	445
Cumulative portion of the houses with at least distance to the toilet facility	0,09	0,31	0,66	1,00

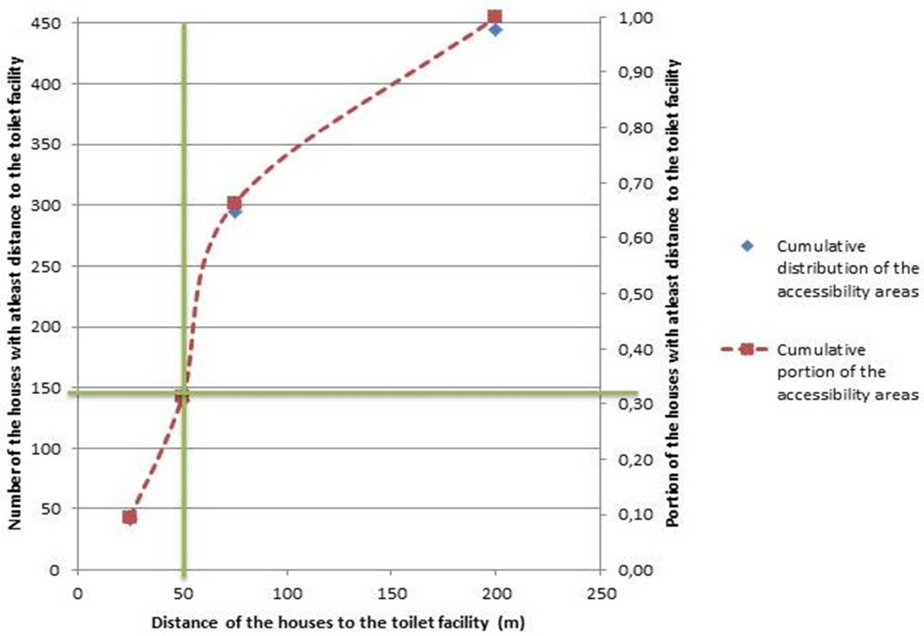


Figure 16: An example cumulative distribution of the number of the houses that fall within different distance radius (blue dots), and cumulative portion of the houses that fall within a certain distance from the toilet facility (red dots). The 50 m distance to the toilet facility is considered as an acceptable distance in this example and the percentage of the houses that fall within this distance can be read using the green lines. This graph is only valid for the example locations presented in Figure 15.

5.1.2. Measures to increase users' accessibility to toilet facilities

To ideally increase the users accessibility to the toilet facilities there are requirements for land and financial resources to construct more number of toilets. The scarcer the sanitation facilities are, the more the influence of accessibility problems can be. Nevertheless, when the available lands do not allow constructing more toilet facilities that are easily accessible a larger number of people, the measures to facilitate people access to toilet facilities shall be taken into consideration. The influence of sanitary engineering practices on this issue may be negligible; rather, the social and institutional arrangements are required to make the sanitation facilities more accessible to users.

A study in Bangladesh shows that in selecting the location of latrines, privacy followed by the ease of access have the highest influence, while health and hygiene issues have much lower influence on the choice of the users for the location of facilities (Kazi and Rahman, 1999). It may be even expected that a socio-culturally defined level of privacy attracts people to a certain facility while there are other facilities existing nearby. In such cases the monitoring programs shall be executed locally in order to enhance insights into people's preferences in using sanitation services. The results can then be used in further phases of sanitation developments, to provide facilities that are more likely to be preferred by the users.

Other possible measures to facilitate people's use of toilet facilities include building pathways to the toilet facilities and illuminating these pathways during the night time (COHRE et al., 2007) to address the physical security issues for women and children. On the other hand, in finance allocation to different areas, decision makers shall prioritize the areas with higher levels of crime to assist people build their own toilets if they have the required space, or build more number of shared facilities that can be used among smaller number of households (COHRE et al., 2007).

The problem of users' accessibility can be more intense in slum settlements that are highly congested and where the public utilities are always more concerned about the temporary nature of people's stay in these areas and their willingness to pay (Jinnah, 2007). Some studies, including one executed in the slums of Dhaka, Bangladesh, show that these communities are actually not very transient and are very much willing to pay also if they were being provided with the public services (Jinnah, 2007). In this example in Dhaka, the NGOs served as an intermediate to fill the gap between the Dhaka Water Supply and Sewerage Authority (DWASA) and residents of the slum settlements, in order to supply services to the people regardless of land tenure status. As the NGOs were registered bodies, the DWASA was willing to deal with them and provide them with the required services. This model may be used as a step towards providing sanitation services to the residents of informal slum settlements in other places as well.

Maintaining people's accessibility to sanitation facilities shall continue after the facilities are constructed, during the whole operation period. Development of physical barriers (e.g. buildings, fences, etc.) at the location of the facilities, in a way that they obstruct users' accessibility to the facilities, shall be avoided. On the other hand, operation of the facilities shall be arranged in a way that users' access is not limited. Facilities that are closed during the night time or the ones that are being attended by very limited number of individuals (who may misuse their authority) are more vulnerable to limiting people's access to the required services.

5.2. Accessibility of reuse centres

Reuse of toilet products (urine, faecal sludge and biogas), as sources of nutrient for agriculture and energy for households, is an interesting option in a world that is facing increasing pressure on its natural resources. This has attracted the attentions towards some sanitation systems that provide the possibility of nutrient and energy recovery from toilet products (e.g. eco-san toilets, bio-latrines).

Although the eco-san facilities have been implemented in several locations since the 70s, they have mostly remained as pilot projects in rural areas (Carlesen et al., 2008). One of the main reasons identified for this low level of success is related to lack of the required link between the toilet owners and the farmers or reuse centres (Letema, 2012; Carlesen, 2008).

In Kampala, Uganda, promotion of eco-san toilets started by SIDA (Swedish International Development Agency) in 2002, with cooperation of Kampala City Council (KCC), aiming at low-income household residing in low land areas of Kampala. In an evaluation report by SIDA in 2008, after 6 years of starting the project, it was revealed that the main aims of the project were not achieved, meaning that eco-san systems suitable and functional for scaling up in poorly sanitized areas of Kampala were not developed (Carlesen et al., 2008). An important reason was mentioned to be lack of proper provisions for collection and transport of the toilet products, meaning that the nutrient loop was not closed (Carlesen et al., 2008). This means that the potential privilege of eco-san facilities compared to normal toilets was not fulfilled in practice.

Letema (2012) also reports from Kisumu in Kenya, where eco-san toilets have been implemented in a few slum settlements, that the facilities are more a 'showcase' rather than a functional system. He also mentions that the link between the toilet facility and the urban farmers are yet to be established (Letema, 2012).

For bio-latrines, which are erected in order to utilize the biogas that can be produced from digestion of the faecal matter, the same concerns of developing the link between production and reuse exist. If the produced biogas is not reused, the main privilege of the system (in comparison with other facilities) is not utilized and the facility will be degraded to a normal pour-flush latrine.

5.2.1. Quantification of reuse centres accessibility

The evaluation of a sanitation facility with regard to recovery and reuse shall be done based on the possibility for the products to reach the reuse centres. Intuitive judgments may incline towards prioritizing ecological sanitation facilities or bio-latrines among other facilities concerning the potential possibility for recovery and reuse. However, the above-mentioned examples indicate that there is a difference between the potential of a system to fulfil a criterion and its fulfilling that criterion in practice. While the former has been mostly used in evaluation of the sanitation facilities, this thesis claims that based on the real experiences, this kind of approach could be misleading and ends up with developing systems that are not fully functional. In that case not only the system privileges (recovery and reuse) are not achieved, but also the main aim of the sanitation facility, i.e. improving public health, is threatened due to piling up of toilet products that are not adequately collected.

In order to differentiate between the potential of a system to facilitate recovery and reuse (of energy and nutrients) and it doing so in reality, an indicator shall be defined with respect to the reuse centres accessibility. The percentage of the recovered products that can actually reach the reuse centres could be a good indicator for a system evaluation regarding recovery and reuse.

Determining the percentage of the recovered products that can reach the reuse centres is based on the available financial resources and the institutional provisions for collection and transport. From the available resources for collection and transport, the decision makers shall determine a distance within which the products could be transported to the reuse centres. For instance, for bio-latrines in Kisumu, Kenya, the implementation is planned in a way that these facilities can serve the residents in 60 m radius from the facility location (Letema, 2012). The 60 m radius is selected so that the piped biogas can be securely and easily distributed among the residents. Similarly, for eco-san facilities, the distance from where it is possible (institutionally and economically) to collect and transport the recovered products to the reuse centres shall be determined by the decision makers.

Once the distances are determined, the percentage of the facilities that fall within the collection and transport coverage area can be derived. This percentage shall be used for evaluation of the system with regard to recovery and reuse.

5.2.2. Measures to increase the accessibility of reuse centres

To increase the accessibility of reuse centres is equivalent to increasing the percentage of the recovered products that can reach the reuse centres with the least possible cost. For this purpose, the location and the capacity of the sanitation facilities in production shall be compatible with the location and the capacity of the reuse centres for consumption. The closer the reuse centres to the production sites, the lower the transportation costs would be.

Carlesen et al. (2008) in an evaluation on the ecological sanitation systems in Kampala, Uganda, state that a model for the collection, transport and reuse of urine and faecal matter is lacking. Upon development and execution of such a model which addresses the management and the economical requirements for collection and transport, the nutrient (and energy in case of bio-latrines) cycle may be closed.

Large scale farmers, who can be the biggest users of recovered products from ecological sanitation systems, can also act as facilitators in collection and transport, where the required institutional arrangements and financial resources are lacking among the official authorities at the state level.

6. Quantification of the Assessments for the Criterion: Reliability

In order to quantitatively assess the sanitation options with regard to the indicators for the criterion of reliability, some methods are developed in this thesis and presented in sections 6.1 to 6.4. Again to be mentioned that these methods are rather developed in order to show that, unlike the first impressions that one (and many experts) might get, it is not impossible to quantify such assessments; and it is not required to turn to qualitative judgments by over simplifying the reality.

6.1. Reliability of water supply

The sanitation facilities that rely on water supply (i.e. the flush toilets) are vulnerable to the possible failures in supply. Although based on the screening stage the flush toilets will be eliminated from the options where no water supply is available, but availability of water supply is not sufficient to assume that the system will always function soundly. In low-income countries, water cut is a frequent event that can impact the function of the flush toilets. Therefore, evaluating the sanitation options that rely on water, with regard to reliability of water supply shall be considered in the decision making process.

In literature, reliability is defined as the ability of a system or component to perform its required functions without failure for a specific period of time. Therefore the reliability for a system can be formulated as: $1 - \textit{the probability of failure of the system}$. So to be able to estimate the reliability of water supply, the probability of water supply failure shall be determined.

6.1.1. Determining the probability of water supply failure via construction of fault trees

In places where a constant water supply is not available daily and certain hours of water cut occur every day, the reliability of water supply on a daily basis would simply be equal to the ratio of the hours that water is available to the total hours per day. In places where water cut is not a normal routine but rather a result of some sudden failure in the water supply system, then the probability of water supply failure shall be estimated using a more detailed analysis.

Fault tree analysis is a top-down failure analysis in which all possible failure mechanisms that may lead to a system failure are identified. Fault trees start with a top event. The top event is the failure that is the subject of analysis. Intermediate and basic events are the events that can cause the top event and can be as detailed as required. The choice on how detailed the basic event shall be is dependent on the level of the detail that is needed for a specific analysis. The basic events are connected to each other and to the top event through AND and OR gates. The AND gate connects the events that must occur simultaneously for the final result to occur, while the OR gate connects the events that are solely enough for producing the result. An example fault tree is presented in Figure 17.

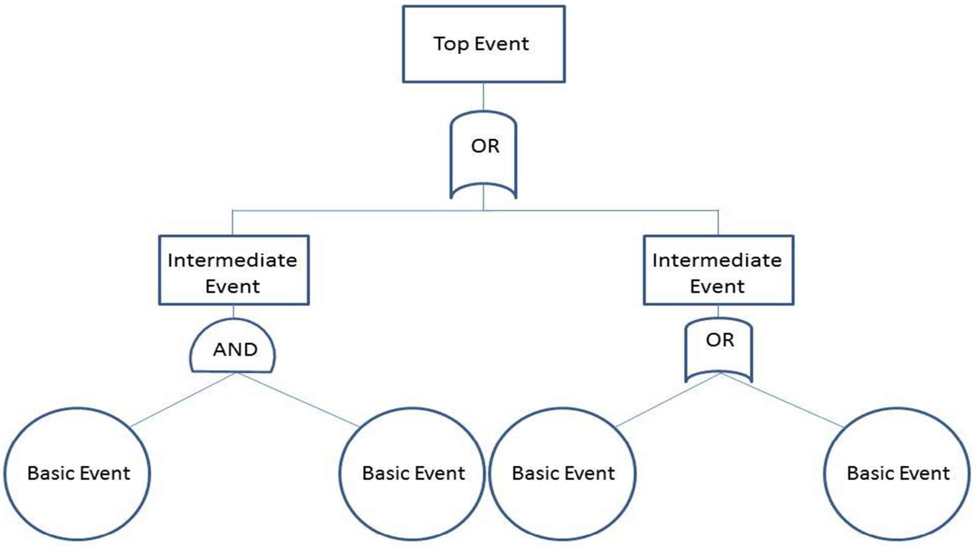


Figure 17: Elements of an example fault tree

To estimate the probability of failure in water supply, the fault tree analysis may be utilized. In this case the top event is the failure in water supply. The basic events, meaning the events that lead to the failure in water supply are: A- failure in one of the system components (e.g. pumps, pipelines, etc.) or B- the water cut due to insufficient supply (insufficient supply is defined as insufficient quantity and/or quality to meet the demands). Each one of these 2 events is also caused by other events but that level of details is not necessarily required in this context. The basic events, in this case, link to the top event via an OR gate since occurrence of each one of them (failure in system components or water cut due to insufficient supply) can alone lead to the failure in water supply. Figure 18 presents the simplest fault tree for water supply failure.

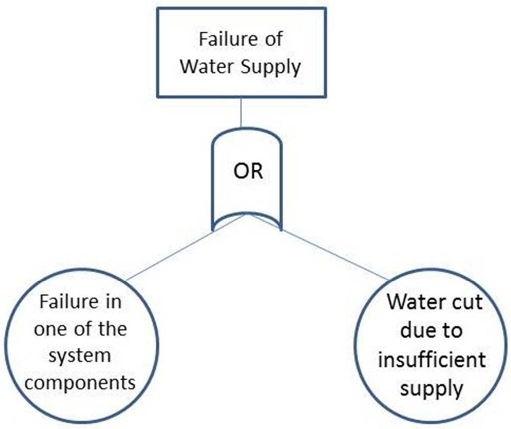


Figure 18: A simple fault tree for failure in water supply. Insufficient supply concerns both quantity and quality aspects.

6.1.2. Quantification of failure probability using the fault tree analysis

In a fault tree analysis, the failure probability of the top event will be quantified by quantifying the failure probability of the basic events. In this regard a probability model shall be chosen which suits the type of the failure events in the fault tree.

In this study, a Poisson probability distribution is chosen for the basic events (failures in system components and water cut due to insufficient supply). The Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time (and/or space) if these events occur with a known average rate and their occurrence in disjoint time intervals is independent of each other. These conditions apply to the failure events that lead to water supply failure. Therefore the probability of failure can be described by:

$$P_r(k) = f\ (k, \lambda t) = \frac{e^{-\lambda t}(\lambda t)^k}{k!} \quad \text{Equation 1}$$

in which k is the number of occurrences, $P_r(k)$ is the probability of k times occurrence, λ is the rate of occurrence and t is the time period under study.

The time period t during which the probably of failure is going to be estimated can be chosen by the decision makers, however it shall be chosen in a way that it suits the frequency of events. A time interval of one week or one month may be a suitable choice in most cases with regard to water supply failure events, in places where a constant water supply is normally available.

The rate of occurrence λ at best shall be derived from failure records over a period of time. However, in most cases these data may not exist as recording the failures may not have been performed systematically. In such cases experts judgments can be an important source of information. These experts may be the water utility personnel or other experts who have experience with such failure events in the location (Lindhe et al., 2010). Interview with people (users) can also be another source of information. They may be asked to estimate the average rate of failure within the chosen time period according to their observations.

Once the average failure rate is determined, the probability of whatever times failure (k = 1,2,3,…) in a time interval of 1 week or 1 month can be calculated using equation 1.

When the probabilities of basic events are calculated, the probability of the top event can be determined considering their connection gate being an AND gate or an OR gate. In case of an OR gate and having 2 basic events (see Figure 18) that are independent of each other, the probability of the top event will be:

$$P\ (A\ or\ B) = P\ (A \cup B) = P(A) + P(B) - \ P(A)P(B) \quad \text{Equation 2}$$

When the number of the basic events that are connected by an OR gate is more than one, the probability of the top event will be:

$$P(X) = 1 - \Pi_{i=1}^{m} [1 - P(x_i)] \quad \text{Equation 3}$$

where $P(x_i)$ is the probability of the basic events and m is the number of the basic events.

With the calculated probability of water supply failure from equation2 (or 3), the reliability of water supply can be derived using: $Reliability = 1 - probability\ of\ failure$.

6.1.3. Measures to increase water supply reliability

Measures that increase water supply reliability are the ones that decrease the failure probability. Decreasing water supply failure probability is only possible through reducing the parameters λ, i.e. the failure rate (see equation 1). If a certain level of reliability is going be maintained, it shall be done via maintaining a certain level of failure occurrence rate.

Decreasing the water supply failure rate is a complicated measure that entails technical, institutional and financial provisions. The failure rate due to failure in one of the system components can be decreased by designing a water supply system that is more robust towards failure in its components. Having spare equipment that can be operated during failure events is a possible solution, but it entails additional costs for the water supply system. Repair and maintenance of the electromechanical equipment can be troublesome in low income countries as the spare-parts are sometimes not available locally and should be ordered and imported from abroad. This procedure is time consuming and expensive and it also requires institutional provisions. Therefore, utilizing equipment for which the spare-parts are more available locally and for which the expertise to repair and maintain is also readily available will reduce the impacts of such failures.

To decrease the rate of the water cut due to insufficient supply, the quantity and the quality of the supplied water shall be improved. This is possible through increasing the intake capacity form the water source, increasing the treatment capacity, increasing the storage capacity and improving the treatment quality. All these measure, however, require additional investments in the water supply systems and improving the institutional capacity that is needed to operate and to maintain them.

Increasing the storage capacity at the users side may also be a measure in areas that routine water cut occurs. Nonetheless, if in-house supply is not available, this means extra burden for the users as they would need to carry larger amounts of water from the supply to their homes or travel more times between the two locations.

6.2. Reliability of users' practices (Users' acceptance)

The function of the sanitation facilities and the fact that they can or cannot fulfil the aims for which they have been developed is affected by the behaviour of the users of these facilities. A study in Dar-es-Salaam, Tanzania, shows that 52% of the users of dry pit latrines bath in the same place as the latrines (Chaggu, 2004). This means that a facility that is designed for working without water will then face a situation in which considerable amount of water is ending up in the pit (causing delay in inactivation of pathogens in the faecal matter, increasing the hydraulic loading rate to the soil that can increase the probability of groundwater pollution, etc.). In another example in Tanzania, it has been revealed that the separated urine from eco-san toilets contained more than 1500 no/100 ml *E.coli*, suggesting that the urine was mixed with faecal matter (Chaggu, 2004), most likely due to incorrect practice of users.

Even with cistern-flush toilets that may seem insensitive to users practices, the facilities may not be used as they are designed to be used. Closing the lid of the sitting toilet during flushing is almost never practiced, resulting in spread of the contaminated aerosols in the surroundings. However, the impact of this incorrect practice may not be detrimental to the general function of the system and may be neglected.

Such examples indicate that unreliable users' practices can impact the expected outcomes of a system. The extent of this impact is dependent on the system type; Eco-san toilets for instance, are very sensitive to careless operation (Winblad and Simpson-Hébert, 2004). Therefore, in choosing a sanitation facility, the extent of its vulnerability to incorrect practices by the users shall be analysed and the reliability of correct practices shall be estimated as an evaluation criterion for that facility.

Usage-centred design processes are characterized by the designers and planners paying specific attention to the interactions of future users with a proposed facility (Rooden,2011). The pitfall however, lies in the fact that there exists a variety of users who will use the facility in a variety of ways.

Although this concept has been widely noticed among designers and planners through various examples from all around the world, its application in the decision making process is still not well-established. This section tries to tackle this issue more closely and finds possible means that can lower the impacts of incorrect users' practices.

6.2.1. Quantification of reliability of users' practices

According to many ergonomists, quantitative prediction of human performance is intractable due to individual differences and many interacting factors in real operation that affect the performance of people (Kirwan, 1996). However, during such prediction attempts, ways of improving people's performance could be identified that leads to overall improvement of system performance.

The reliability of users' practices can be quantified by estimating the probability for incorrect usage, i.e. the probability that users do not use the facility as it is designed to be used. This is similar to Human Error Probability (HEP) definition (see equation 4) which is used in Human Reliability Assessment (HRA). HRA deals with assessment of human errors potential in a system (Kirwan, 1996).

$$HEP = \frac{Number\ of\ erros\ occured}{Number\ of\ error\ opportunities} \quad \text{Equation 4}$$

By simulating the definition for HEP, the probability of incorrect use of sanitation facilities by the users could be defined as:

$$Probability\ of\ incorrect\ usage = \frac{Number\ of\ incorrect\ practices\ that\ occur}{Total\ number\ of\ incorrect\ practices\ opportunities} \quad \text{Equation 5}$$

The reliability of users' practice will be: $1 - Probability\ of\ incorrect\ usage$.

Incorrect usage of sanitation facilities may be broken down into various scenarios (opportunities) of incorrect practices by the users, depending on the type of the facility under assessment. For each sanitation type, there can be several possible scenarios for users incorrect behaviours that are not compatible with the system nature and will impact its intended function negatively (e.g. for dry latrines: bathing in the same room of dry pit latrines, emptying grey water in the dry pits; e.g. for eco-san toilets: defecating in urine hole).

A possible method of achieving an approximate value for the probabilities of incorrect usages is through monitoring programs that observe users' behaviour in cases where that facility has been applied. In development process of Friendly Rest Rooms (FRR), an EU project that aimed at making toilet facilities better suited for disabled and elderly people, when information was needed regarding the users preferences, several methods were applied. One of the methods was observation of users behaviour by asking them to pretend using the toilet facility as they would normally use (Dekker et al., 2011). Another way of getting information was through questionnaires that had to be filled by the users regarding their habits, preferences and requirements in using the toilet facilities (Dekker et al., 2011).

The questionnaires that address people's behaviour in using a facility can provide quantified insight into the needs and normal practices of the users (Dayé, 2011). They can also provide insight in to (cultural) differences in people's practices and assess the frequency of various behaviours (Dayé, 2011).

The pitfall however, is in the prediction of a value for the probabilities of incorrect practices by the users prior to application of the facilities in the area under study. In this case, monitoring results from another location where the facilities have been applied earlier shall be used. However, people's behaviour in a location may be (to some extent) representative of people's behaviour in another location if the socio-cultural determinant factors are similar between the two places. Therefore, the population that is going to be chosen for evaluation, at best and if possible, shall be within the same society (e.g. a near-by and socio-culturally similar area within the same society where the sanitation facility has been developed earlier).

It should be noted that using similar cases for prediction of another case may impose a large uncertainty to the results. This uncertainty increases as the socio-cultural differences between the groups increase. The real results after implementation of a facility may even deviate largely from the predictions. In spite of this shortcoming, the use of this method is inevitable under the situation where no other estimate of users' acceptance and behaviour is available. However, the impacts of wrong predictions can be reduced by increasing the likelihood of users' acceptance on sanitation facilities as described in section 6.2.2.

If a structured monitoring program cannot be performed, experts judgment may be used in which experts are asked to estimate the probabilities of particular scenarios.

Once the reliability of users' practice has been quantified, the impact of incorrect practices may also be analysed for different scenarios. These impacts are dependent on the system type and the surrounding conditions and are not particularly addressed in this thesis; but some of these impacts can already be quantified using other sections in this report. For instance, the risk of groundwater pollution arising from using water in dry latrines can be quantified using the procedure explained in section 4.1.

6.2.2. Measures to increase users' acceptance on sanitation facilities

Increasing users' acceptance on different technologies or facilities has been in many cases tackled by providing users' training. Although training can be a means of increasing awareness and impacting people's behaviour, but some evidences show that people will only accept the changes that fit into the overall organization of their households and lifestyles (Spaargaren and van Vliet cited in Krantz, 2005). Cultural standards of comfort, cleanliness and convenience play an important role in this regard (Krantz, 2005; Shove, 2003). Krantz (2005) in a study on changing the routines by changing the water and sanitation arrangements revealed that a culturally determined minimum level for comfort, cleanliness, and convenience exists which does not change much over time, irrespective of other possible incentives that may be introduced to the society. She concluded that only solutions that provide that level (of comfort, cleanliness and convenience) would fulfil the expected outcomes.

Therefore, the likelihood of users' acceptance and correct use of sanitation facilities can be increased by utilizing the facilities that are most compatible with the socio-cultural standards of that society and can maintain the minimum levels of comfort, cleanliness and convenience as defined by the society. In some cases it may be even possible to modify the sanitation facilities in such a way that they can adapt to the preferences and requirements of the users. An example of such adaptations is with regard to eco-san facilities in Kerala, India, and in Palestine. In those cultures, washing after defecation is culturally and religiously mandated, while eco-san toilets are originally designed to work as dry facilities. To adapt to the requirements of the society, eco-san toilets in those locations were designed with an additional trough over which anal cleaning could be performed and the water would then be directed to evapo-transpiration beds or septic tanks (Winblad and Simpson-Hébert, 2004).

There may be situations where maintaining the current routines is not preferred by the decision makers, but rather a change and shift in the norms and standards is aimed at. In such cases it should be understood that technical solutions alone, regardless of socio-cultural and socio-economic factors will not be sustainable. Social sustainability includes practices that are socio-culturally acceptable, affordable and that users find comfortable (Kranz, 2005). Furthermore, the extent of the changes in the arrangements shall be large enough to result in a radical change in the routines of the people (Kranz, 2005). There may exist a threshold below which the physical changes that are introduced to the society will not be able to create a shift in users' behaviours.

Either the sanitation facilities are aimed at maintaining the norms and standards of the society or are aimed at changing them, a monitoring program following the implementation of the facilities will enhance insight in to people's confrontation with those systems and facilitates further variations and modifications in the systems arrangements.

Apart from the measures that shall be taken to decrease the likelihood of incorrect usage of the sanitation facilities, other measures are also required to decrease the negative impacts of such incorrect uses if they happen. For instance, if users' behaviour with regard to dry latrines is not completely reliable and water may end up in the pits, there should be measures to decrease the probability of groundwater pollution in that case. Building sand envelops or increasing the distance of the pits to the public wells (see section 4.1.4) shall be considered, based on the risk levels that the decision makers are going to maintain, in a trade-off with increased costs.

6.3. System maintainability

Like for many other technical interventions that are implemented in low-income countries, provisions for operation and maintenance (O&M) of sanitation facilities are often overlooked during the decision-making process. Technical criteria and initial investments have been the points of main emphasis in choosing a technology for many years (Brikké and Bredero, 2003). Sanitation projects are in many cases viewed as ended once executed, regardless of the fact that the benefits that they bring to the society actually starts after the projects are implemented. In fact, once the systems are constructed, it is the O&M practices that determine the level of the benefits that a system can bring about for the users (see Figure 19). Therefore, to ensure that these benefits are achieved, the projects must be sustainable and the O&M provisions should be integrated into the project development from the start (Brikké and Bredero, 2003).

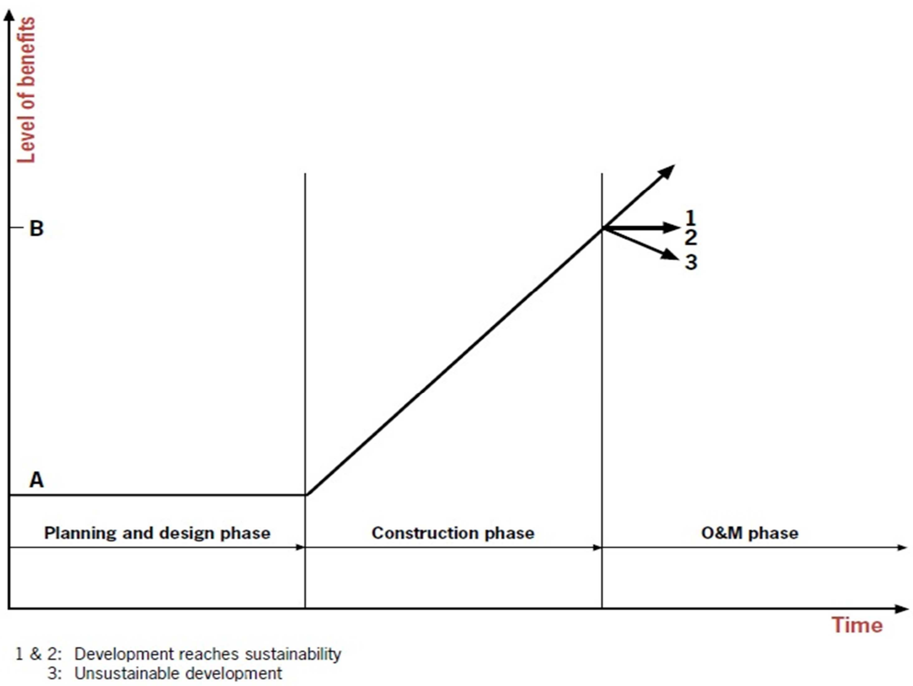


Figure 19: Sustainability in the project cycle (Adapted from Brikké, 2000)

Operation and maintenance practices are no longer considered as purely technical matters, but rather encompassing social, institutional, cultural, economic and environmental issues. Brikké (2000) recognizes 4 major factors that contribute to sustainability through an effective O&M practice. These factors are: 1) technical factors, 2) community factors, 3) environmental factors and 4) legal and institutional framework (see Figure 20). The intersection between the technology and the community forms the degree of ownership, which also defines the responsibility of the community towards the O&M practices. The intersection between the community and the environment indicates the influences of the community on the resources and how the community behaviour influences the environment and vice versa. The intersection of technology and environment indicates the risks that may arise from the technology to the environment and how the technology itself may fail or succeed under the environmental impacts. The intersection of technology, community and environmental factors determines the sustainability of the system, while all these factors evolve within a legal and institutional framework.

Figure 20: Factors influencing effective O&M and sustainability of a system (after Brikké, 2000)

Typically, management models range from highly centralized governmental to localized community based. A common model for O&M management has the central government agency as the first tier, the local government agency or private sector as the second tier and the community organization on the third tier (Brikké and Bredero, 2003). In the recent years there has been the tendency to decentralize the O&M practices and to involve the community, while the governments shift from traditional service providers to facilitators of service provisions (Brikké and Bredero, 2003). The appropriateness of this approach is nonetheless controversial. Black and Fawcett (2008) for instance, point out that the sanitary revolution in developed countries could only speed up and achieve large coverage in the societal level when the public sector got fully involved and took actions. They question the new approach which promotes privatization of the sanitation systems management. Although this trend could increase the flexibility of O&M activities and reduce expenses of the governments, but low profit margins would limit the private sector involvement. On the other hand, the private sector accountability in fulfilling the needs of the society is also a concern, especially in absence of effective monitoring and control programs (Brikké and Bredero, 2003).

There seems to be a consensus in the empirical research that a positive and strong incentive for good O&M practice is the degree of ownership on the assets (Balakrishnan, 2010). With the increased degree of ownership as a variable, the effectiveness of maintenance activities is likely to increase (see Figure 20) and one can assume a logarithmic growth for that. However, there are cases that indicate that the environmental factors can neutralize the impact of the degree of ownership on the effectiveness of O&M activities. Balakrishnan (2010) in a study in 2 tenements within the same municipality in India reveals that the tenement which had almost double the percentage of renters compared to the other tenement, which had more owners, had in fact a considerably more effective O&M activities going on for the sanitation systems and the system was maintained in a much better condition. In the second tenement, i.e. the tenement with poor maintenance of sanitation facilities, the authorities had intentionally changed the properties rights policy from renting to 'rent-to-purchase' , where the residents could become the owners of the properties within a few years. The intention was in compliance with the idea that increased degree of ownership will motivate the maintainability. However, the results were unexpected. The study indicated that the location of the main sanitation facilities (septic tanks in this case) had the major impact on the incentives of the community to perform O&M practices. In the tenement with effective O&M activities, the septic tanks were located in the centre of the housing blocks, where people pass every day to enter their houses and where the children play. In the other tenement, the septic tanks were located in a back alley between the housing blocks where there are hardly any passengers or direct viewers.

Such studies indicate that although there are recognized variables that contribute to the success or failure of system management, but there are always unexpected variables that contribute to that as well and the uncertainty of the evaluations in the decision-making process shall always be taken in to account.

6.3.1. Quantification of maintainability and maintenance costs

Maintenance, as defined by Dhillon (1999), is the measures taken to keep a product (or facility) in operable conditions or to repair it to the operable conditions. Corrective maintenance (CM) is any unplanned maintenance that is carried out when the system fails; while preventive maintenance (PM) is any planned maintenance that takes place when the system is still operating (Pham and Wang, 1996).

While reliability is the probability that the failure does not occur in a specific time period, maintainability is the probability that the required maintenance will be successfully completed in any given time period (Dhillon, 1999). Maintainability may be measured by combining the frequency of maintenance, elapsed maintenance times, labour hours, required material and equipment, and the maintenance costs (Dhillon, 1999; Brikké and Bredero, 2003).

In order to be able to evaluate the required O&M practices quantitatively, a table (factsheet) could be developed for each of the sanitation facilities. The tables shall list the required O&M activities for that particular sanitation facility, the required frequency of the activities, the type and the amount of the material and spare parts that are needed, the type and the amounts of the tools and equipment that are needed and the required human resources. An example factsheet for O&M of ventilated improved pit latrines is presented in Figure 21.

Estimates on the items to be included in the O&M factsheet may be derived from the previous experiences in the same region. There is also some literature that provide such estimates for O&M of sanitation facilities such as some WHO documents (e.g. Brikké, 2000; Brikké and Bredero, 2003). Guidance from manufacturers may also be used. However, in using all these data, local conditions shall be taken in to consideration and using only 'standard' values shall be avoided.

Activity	Frequency	Human resources	Materials and spare parts	Tools and equipment
Clean drop hole, seat and superstructure	Daily	Household	Water, soap	Brush, bucket
Inspect floor slab, vent pipe and fly screen	Monthly	Household		
Clean fly screen and vent inside	Every one to six months	Household	Water	Twig or long bendable brush
Repair slab, seat, vent pipe, fly screen or superstructure	Occasionally	Household or local workers	Cement, sand, water, nails local building materials	Bucket or bowl, trowel, saw, hammer, knife
Dig new pit and transfer latrine slab and superstructure (if applicable)	Depending on size and number of users	Household or local workers	Sand, possibly cement, bricks, nails and other local building materials	Shovels, picks, buckets, hammer, saw, etc.
Switch to other pit when pit is full	Depending on size and number of users	Household or local workers		Shovels, buckets, wheelbarrow, etc.
Empty pit (if applicable)	Depending on size and number of users	By hand: household or local workers (not recommended)	By hand: water	By hand: shovel, bucket
		By mechanical means: specialized service	By mechanical means: water, spare parts for machinery	By mechanical means: pit-emptying equipment

Figure 21: Example fact sheet for O&M of ventilated improved pit latrines (Adapted from Brikké, 2000)

Once the factsheet is developed, it provides the required insight to quantify the amount of the time and the costs that are required for O&M activities.

Mean Time to Repair (MTTR) is the corrective maintenance time, i.e. the elapsed time needed to perform a maintenance activity. It takes in to account the whole repair cycle from fault detection to fault isolation, disassembling, repair and reassembly (Dhillon, 1999). MTTR can subsequently be used to calculate the system availability and down time.

MTTR for a system can be calculated by:

$$MTTR = \frac{\sum_{i=1}^{m} \lambda_i T_i}{\sum_{i=1}^{m} \lambda_i} \quad \text{Equation 6}$$

where m is the number of the maintenance tasks for a system, λ_i is the constant failure rate (failure frequency) of unit i, and T_i is the corrective maintenance time needed to repair unit i.

For preventive maintenance activities such as inspection and calibration, the mean preventive maintenance time can also be calculated using a similar equation as for the mean corrective maintenance time.

Total maintenance time includes not only 'active' corrective and preventive maintenance times, but also the administrative and logistic delay times (Dhillon, 1999). Administrative delay time is caused by administrative constraints or priorities. Lack of proper institutions to manage the maintenance activities will add to the administrative delay time. Bureaucracy and centralized management systems contribute effectively to the administrative delay time. Logistic delay time is the time spent waiting for a resource (such as a spare part or a facility) to be provided. If the spare parts are not available locally and if the financial resources to supply them are not readily accessible, the logistic delay time is likely to increase drastically. Therefore, the system down time can be calculated by summation of the active corrective maintenance time, active preventive maintenance time, the administrative delay time and the logistic delay time.

In practice, various probability distributions may be applied to a system's repair time data. For a system which is already in place, these data can be collected from the field, while for new systems the data from previous similar experiences may be used. In using the repair time data from another case, it should be noted that the institutional capacities, the available financial resources and the local conditions are determinants of the repair time and the data from one location may be applicable to another location only if these determinants are similar between both locations.

Exponential distribution is assumed for repair time distribution of systems that have a rapid remove-and-replace maintenance, while normal distribution is assumed for many mechanical or electro-mechanical equipment (Dhillon, 1999). Once the repair time distributions are recognized, the corresponding maintainability functions may be applied to them. The maintainability functions, m(t), are used to predict the probability that a repair which has started at t=0 will be completed in time t:

$$m(t) = \int_0^t f_r(t)dt \quad \text{Equation 7}$$

where $f_r(t)$ is the probability density function of the repair time.

If the repair time data for a system have a normal distribution, the probability density function will be expressed as:

$$f_r(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2] \quad \text{Equation 8}$$

where μ is the arithmetic average of the maintenance times and σ is the standard deviation of the variable maintenance times around the mean value.

By inserting equation 8 in to equation 7, the maintainability function will be:

$$m(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^t \exp[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2] \quad \textbf{Equation 9}$$

In comparison among different sanitation systems with regard to the maintainability criteria, equation 9 may be used for evaluation purposes as it provides an estimate of how much time is likely to be elapsed for maintaining a system. If an effective institution which can handle the maintenance tasks quickly and efficiently is not in place, the repair times are likely to increase, due to the administrative delay. In this case, the probability distribution of the repair times will be shifted towards larger times and consequently the maintainability values for any given time period will be decreased. Also if the logistic delay times are large, due to lack of financial resources or long distance between the spare parts supply and demand sources, the maintenance times and system down times will increase and the maintainability values will be affected inversely.

Maintenance cost is an important factor which can highly impact the repair times and consequently the maintainability. This is of significant consideration when the financial resources for operation and maintenance activities are scarce and all the required maintenance costs may not be indulged completely and on time. Sometimes the maintenance activities have to be prioritized in order to meet the available costs. In this case the repair times are likely to increase and the maintainability is expected to decrease.

Using the factsheet tables, the maintenance costs can be determined knowing the required maintenance frequency, the required material and equipment cost and the cost of labour-hour that is used for maintenance tasks (Brikké and Bredero, 2003). The material and equipment cost shall be enquired locally. The annual mean maintenance labour-hours can be calculated using the equation presented by Dhillon (1999) as below:

$$MLH_a = \frac{T_{S\,(MTTR)(N_C)}}{MTBF} + T_p.N_p \quad \textbf{Equation 10}$$

where MLH_a is the mean maintenance labour-hour per year, T_s is the number of the operating hours per year, *MTBF* is the mean time between failures, *MTTR* is the mean time to repair, N_c is the mean number of persons needed to perform a corrective maintenance task, T_p is the annual mean preventive maintenance time, and N_p is the mean number of persons who perform preventive maintenance.

While working with the mean values in equation 10 in a deterministic way may give good estimates of the required labour-hours and consequently the maintenance costs, but the uncertainty in any of the parameters in equation 10 may lead to different results. The impact of the uncertainty in the values of these parameters on the total costs could also be the subject of analysis for planners and decision makers.

The calculated annual operation and maintenance costs shall be compared with the available annual O&M budget. This budget may be provided by governments, local agencies, private sectors investments, donors or other financial resources. These possible resources shall be identified and the amounts of the money that may be provided by them shall be estimated and evaluated on their stability over a length of time. Then, a probability distribution may be devoted to the possible amounts of available annual O&M budgets. The monetary maintainability function shall then be defined as:

$$m\ (c) = 1 - \int_0^c f_r\ (c)\ dc \quad \text{Equation 11}$$

where $f_r(c)$ is the probability density function of the available annual O&M budgets. Monetary maintainability expresses the probability that the available O&M budget exceeds a certain value of c. The value of c shall be set at the required annual O&M costs that have been previously calculated using the facilities factsheets. In this way the probability that the available annual O&M budgets indulge the required annual costs will be estimated for different systems.

6.3.2. Measure to increase maintainability

The challenges facing the maintenance managers, as described by John Moubray (cited in Banerji, 2007), are:

- to select the most appropriate techniques to deal with failures
- to do it in the most cost-effective way
- to do it with active co-operation of those involved.

However, it may not be possible to simultaneously indulge all these criteria to their maximum. There should always be a trade-off between the acceptable levels of reliability and the resources that are required to attain them. A balanced approach that addresses all the above factors in an optimal way can determine the success or failure of the system maintenance. The key to a cost-effective asset management lies in finding the lowest maintenance cost in the resource-reliability balance curve, that can be met by the available maintenance budget (Banerji, 2007). This is illustrated in Figure 22 in which each of the reliability levels require a certain balance between the (preventive and the corrective) maintenance costs and the tasks frequency. By knowing the available annual maintenance budget (see section 6.3.1) it is possible to estimate the highest achievable reliability level with a specific tasks frequency. If the maintenance budget can be increased, higher reliability levels will also be achievable (see Figure 22).

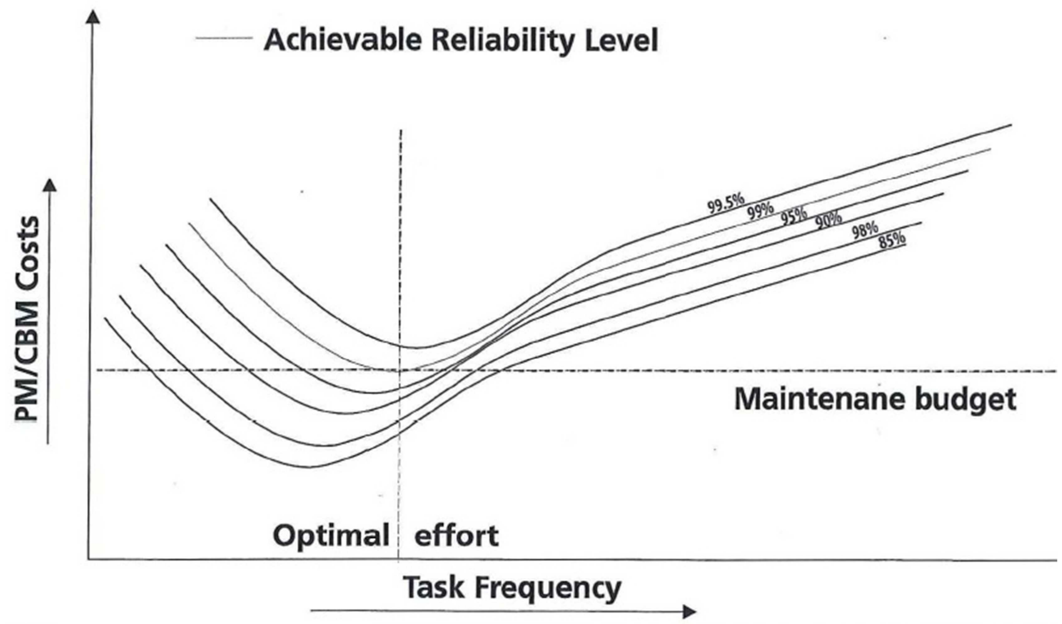


Figure 22: Resource-reliability balance curves (Adapted from Banerji, 2007)

The 'portfolio approach', as the core of the world class asset management, recommends that the assets (the components of the sanitation system in this case) shall be grouped based on their criticality and their maintenance cost. The assets in each group will then require a common management strategy (Banerji, 2007). Figure 23 illustrates a possible classification of the assets into 4 groups:

1): the ones with high impact on the whole system performance and with low maintenance costs. The management strategy for them shall include applying high maintenance frequencies and monitoring closely to ensure that any possible defect or failure is detected quickly.

2): the ones with high impact on the whole system performance and with high maintenance costs. This equipment shall be the subject of preventive maintenance to reduce the failure possibility or to post-pone it, in order to minimize the corrective maintenance costs. They should also be monitored closely so that any defect is detected quickly.

3): the ones with low impact on the process and with low maintenance costs. This equipment shall be maintained reactively when needed.

4): the ones with low impact and with high maintenance costs. The maintenance frequency for these assets shall be rationalized and it may even be advisable to take risks as the negative impacts of the failure may not justify the high maintenance costs.

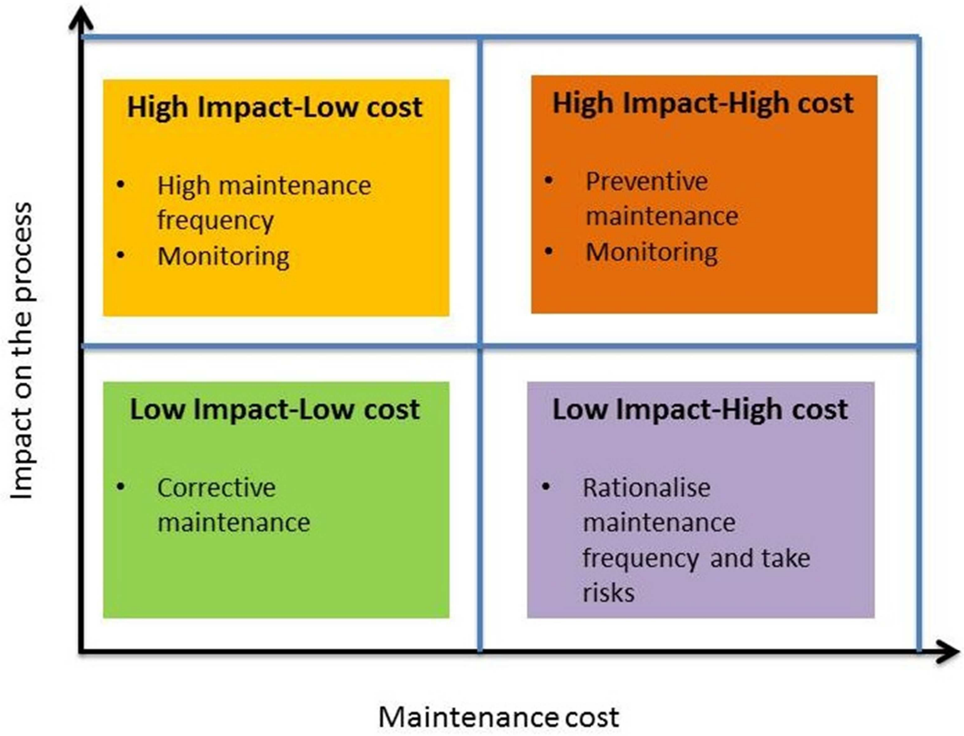


Figure 23: The criticality -cost matrix

In evaluating different sanitation options for decision-making, such a classification of the system components for each option will provide a more clear insight into the required O&M services for that system. It will then be identified what service level will be required for each sanitation option. The required costs, the required O&M tasks frequency and the required institution to perform the O&M tasks will be determined for each option in its local context. In this way, before opting for a technology, the mechanisms for supplying the required O&M services will be predicted and (in an ideal case) established before implementation of the system.

6.4. Proneness to flooding

In flood prone areas of low-income countries, flooding impacts the sanitation facilities by making them inundated and by cutting users access to them. Studies in flood prone areas of Bangladesh reveal that during the flood events all the latrines in the study areas were inundated by flood water (Kazi and Rahman, 1999; Shimi et al., 2010). Floods also cause loss of the latrines capacity and their overflow, leading to environmental contamination (Kazi and Rahman, 1999).

When people's access to sanitation facilities is disrupted due to flooding, they are forced to change their defecation practices (Shimi et al., 2010). During the floods in Bangladesh in 1998 and 2004, 97% of the toilets became unusable and 3% remained partially useable (Shimi et al., 2010). The majority of people in those cases practiced open defecation or built temporary hanging latrines that were connected to the water bodies; while the minority of people used relatives' latrines that were still usable (Shimi et al., 2010). This means that the majority of people were contributing to contaminating their environment and the water sources during the flood events (see Figure 24).

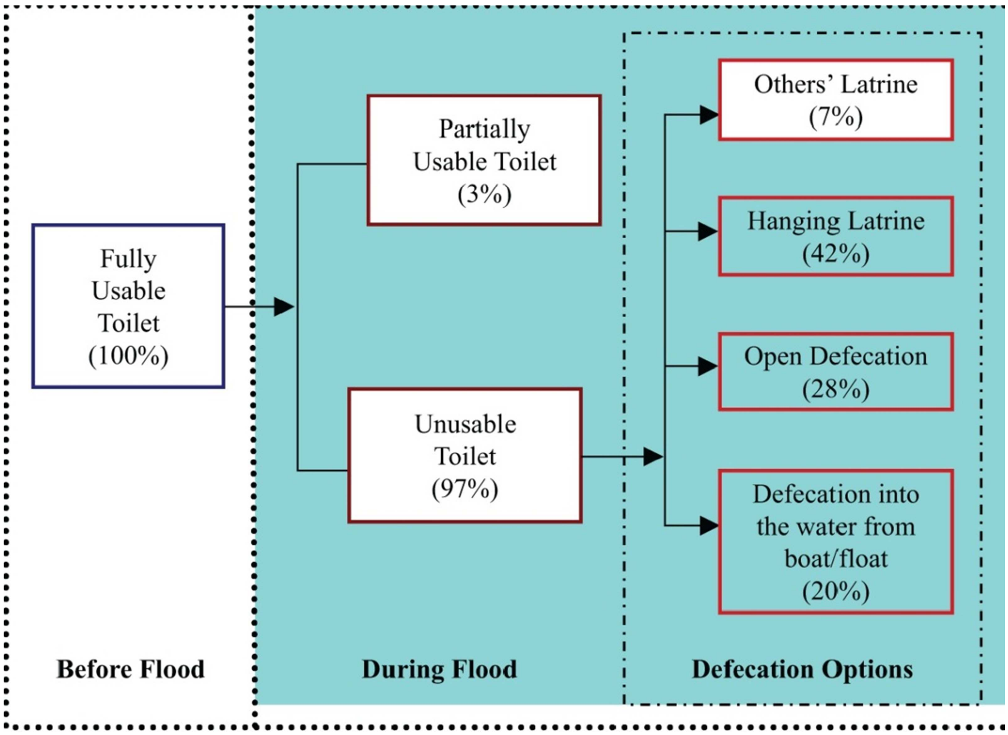


Figure 24: State of toilet facilities and people's defecation practices before and after the floods of 1998 and 2004 in Bangladesh (Adapted from Shimi et al., 2010)

Lack of access to sanitation facilities during the flood events along with overflow of the content of these facilities to the environment, imposes health risks to the population. Diarrhoea and other water borne diseases have been recognized to be caused by inaccessibility to sanitation facilities and polluted drinking water sources during flood events (Heierli cited in Shimi et al., 2010; ten Veldhuis, 2010).

6.4.1. Quantification of proneness to flooding

Flooding can be caused by rainfall runoff, by coastal tides or by rivers overflowing their banks. A combination of these may also occur. Flood models have been developed to understand and manage the flood mechanisms; however such a detailed study which also has its various drawbacks (see ten Veldhuis, 2010) is not presented here. Rather, a practical method will be introduced through which the proneness of sanitation facilities to flooding can be to some extent quantified, using the flood depth data in the area under consideration. As these data are scarce in many cases, quantitative assessment of flooding has sometimes been replaced by qualitative assessment of expected flood frequencies and damages (ten Veldhuis, 2010). In this thesis in contrast, quantitative assessment will still be aimed at and a method is presented through which the problem of flood depth data scarcity may be tackled (see section 6.4.1.2).

The factors determining a sanitation facility proneness to flooding consist of the flood depth, the flood frequency and the location and characteristics of the facility, in particular, its level on the ground. Therefore, in estimating the proneness to flooding, the percentage of the times (or frequency) that the flood depth in an area exceeds a certain level (this level is determined by the sanitation facility level) shall be quantified. The probability of exceedence may then be used as an evaluation criterion and measures to decrease the value of this probability may be considered.

It should be noted that the proneness to flooding is not always associated with the flood depth alone. In sloped areas, the flood flow down the slopes due to the gravitational forces can exert damaging forces to the structures located on these slopes, even if the flood depth is not too much. The magnitude of these forces is determined by the flow velocity and the shape of the structure. Flowing objects (e.g. debris) coming with the flood water can also impose damages to the structures. However, the proneness to structural flooding damages is rather a structural design concern and is not mainly related to the sanitary engineering practices in selection of a facility type. Thus, this point is not further discussed here but rather should be taken in to account once the facilities are going be structurally designed and constructed.

6.4.1.1. Estimating the probability of exceedence using flood depth data

When the flood depth data is available for flood incidences over several years in an area, they can be used to compute the percentage of the times that an arbitrary flood depth is exceeded. To do so, the depths shall be ranked in descending order. If similar values exist, the rank shall be increased with increasing number of similar values. The probability of exceedence is calculated using:

$$p = \frac{m}{n+1} \qquad \text{Equation 12}$$

where m is the rank number of the flood depth, and n is the total number of available data.

The flood depths can then be plotted versus the percentage of the times that flood depths are exceeded. This plot will have a shape similar to the one in Figure 25.

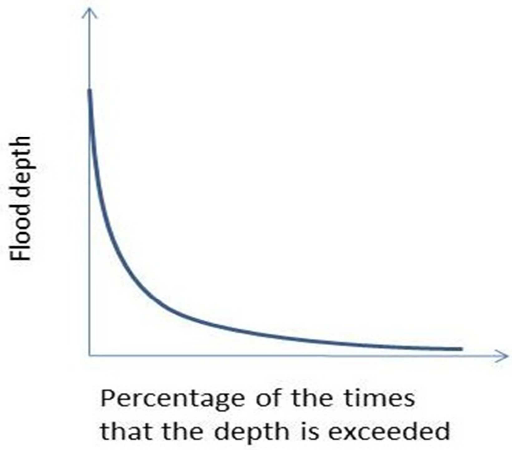


Figure 25: Common shape of flood depth exceedence frequency curve

To be precise, these curves only apply to the period for which they are derived. If the data set belongs to a long period (e.g. more than 10-20 years) they can be regarded as a probability curve which can be fairly used to predict the future conditions (Savenije, 2006).

The data for flood depths may be derived from monitoring networks. However, even if these monitoring networks exist in an area, they may work well under normal conditions but in many cases fail during extreme flood events (Savenije, 2006). Under this situation flood mark surveying, after the flood peak has passed, may be a way of estimating the flood depths. A flood mark can be a mud sign remaining on a bridge, on a pillar or on the buildings (Savenije, 2006).

A simple but very useful method of recording the flood depths has been applied in the Netherlands; that is by recording the flood depths and date on the buildings that are likely to exist for many years or even centuries. Signs of flood depths on the buildings of old churches in the Netherlands have been used as a source of information for flood studies (van Gelder, 2000). Such accurate historical data of extreme events may be almost as valuable as a systematic gage record (van Gelder, 2000).

6.4.1.2. Estimating the probability of exceedence when no flood depth data is available

In cases (that happen often) when no record of flood depths is available, a rule of thumb which utilizes the extreme value theory of Gumbel may be used to quantify the cumulative probabilities of exceedence (p) and non-exceedence (q, where $q = 1 - p$). The extreme value theory of Gumbel models the distribution of extreme events (such as floods). Based on that, the cumulative probability (q) that any of the extreme events will be less than a given value is an exponential function. Therefore, the annual rainfall extremes or flood events tend to plot as a straight line on extreme-value probability (or Gumbel) papers (Savenije, 2006).

To estimate the line which relates the flood depths versus the probability of non-exceedence on a Gumbel paper (see Figure 26), minimum two points shall be specified. These points can be derived from field interviews (Savenije, 2006). People shall be asked to determine the largest flood events that they remember. They shall be asked to specify the year that the events have happened and the levels of the floods (by indicating on the their own height, the trees, the house walls, etc.). For example, if the flood event they refer to belonged to 20 years ago, the frequency of that event shall be set at $p = 1/20$ and the probability of non-exceedence will be: $q = 1 - \frac{1}{20}$.

Apart from interviews, other field observations may also be used to fix one point on the Gumbel probability paper. For river flooding for instance, Savenije (2006) suggests using the bank-full level with the frequency of exceedence of one in 1.5 years (so $q = 1 - \frac{1}{1.5}$). He explains that the logic behind this is that the natural bank elevation is maintained at a level where it is regularly replenished by alluvial sediments.

By plotting the flood depths vs. the probability of non-exceedence (q) on a Gumbel paper, a graph such as the one presented in Figure 26 will be derived that can be used to estimate the proneness to flooding.

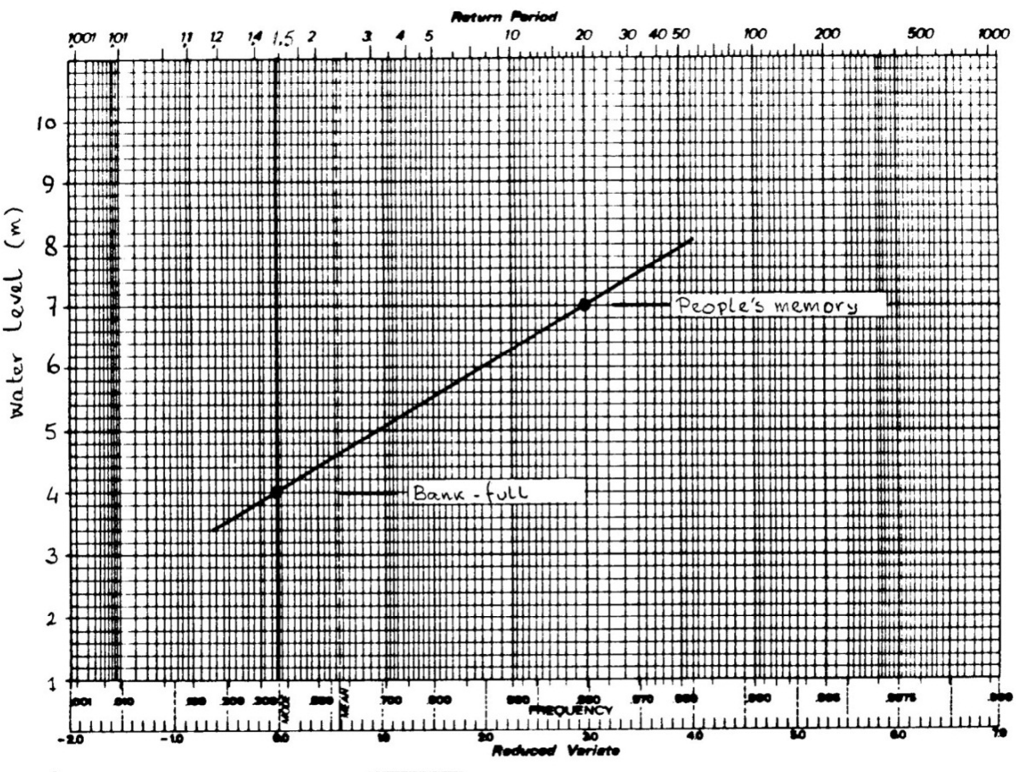


Figure 26: An example for Gumbel distribution of flood depths based on field interviews (Adapted from Savenije, 2006)

6.4.2. Measure to decrease the proneness of sanitation facilities to flooding

Raising the structure of the toilet facilities to above the high flood levels may prevent the inundation of the facilities during flood events. Raised pit latrines have been developed based on the this idea to avoid submergence of the latrines in flood events (Franceys et al., 1992; Kazi and Rahman, 1999; Shimi et al., 2010). However, the drawback is the increased construction costs. In Bangladesh, the construction costs of raised pit latrines is reported to be almost double the cost of traditional pit latrines (Kazi and Rahman, 1999). Furthermore, raising the latrine structure may impose difficulty of access to some users, specifically children and elderly people.

Using sand envelops around the pit of the latrines is introduced as a measure to prevent flushing of the contamination from pits to the groundwater during the flood events in areas where the ground water table is high (Franceys et al., 1992, Kazi and Rahman, 1999). This measure, apart from increasing the construction costs, adds the demand on maintenance of the system as there will be a need for replacing the sands. As the sand pores get blocked over time, the infiltration process will be affected and therefore new sand layers shall be provided.

7. Quantification of the Assessments for the Criterion: Sustainability

When a sanitation facility is going to be implemented in an area, not only the present technical, environmental, societal and financial conditions at the location shall be examined and analysed, but also the dynamics of the surrounding conditions must be taken in to account. If a facility can function as it is planned under the present conditions, it may not do so in the future if these conditions change. Therefore, the changes that may occur in the technical, environmental and social arrangements during the design life of the facilities must be considered and their impact on the system must be predicted.

A sustainable sanitation option, as defined in this thesis, is a sanitation option that continues functioning towards fulfilling the objective that it was designed for (i.e. providing some level of protection against direct contact with human wastes with an outlook for improvement of public health) during its design life time.

In order to quantitatively assess the sanitation options with regard to the indicator for the criterion of sustainability, some methods are developed in this thesis and presented in section 7.1.

7.1. Compatibility with population growth and/or prospective water supply coverage

A type of facility may be functioning as it is designed for according to the expectations but may become problematic once the surrounding conditions change. One of these dynamic conditions is the number of the population who use a sanitation facility.

With the increased usage of sanitation facilities, they will be overloaded more frequently. If the system has some kind of storage capacity (e.g. sludge storage in the pits or in septic tanks) it will be filled more quickly and there will be a more frequent emptying (de-sludging) requirement. If there exists a treatment plant, it will be overloaded and the treatment efficiency reduces.

To deal with the increased loads on the sanitation systems, increasing the system capacity and the O&M activities shall be considered. This, however, requires new financial resources and new or expanded institutions for management. This issue shall be taken in to account when choosing a sanitation facility, so that, ideally, it can cope with the future conditions during its design life.

Another dynamic condition that can impact the sanitation facilities is availability of piped water in a location where there was no or limited piped water supply when the sanitation systems were designed. The volume of the produced sullage (greywater) is very much dependent on the amount of the water supply. Urban household who use a public tap or well for their water demands consume around 20-30 litre per person per day water for cooking and washing, out of which about 80-90% turns in to greywater (Mara, 1996). If in house yard tap is available, the value increases to 80-90 lit/pe.d (Mara, 1996).

In an example from Dar-es-Salaam in Tanzania, the majority of users of dry latrines bath in the same room where the latrine is located or empty their bathing water in the latrine pits (Chaggu, 2004). Based on this example, where people might bath in the latrines rooms, the pit infiltration area shall be designed to cope with the bathing water or the anal cleaning water that might end up in the pits (Franceys et al., 1992). However, if piped water supply is introduced in the house, the amount of the produced wastewater may exceed the values that the system is designed for. In this case, a rearrangement in the system will be required to handle the new sullage flows.

Disposal of sullage flows can happen by pouring it on the ground in the yard or outside the house, where it partly evaporates and partly percolates in to the soil (Franceys et al., 1992). Soil type should ensure that infiltration can take place and sullage does not remain on the ground. Rocky soil or paved areas will prohibit the infiltration and this method of sullage disposal should not be practiced.

Another way of handling sullage flows is by building soakage pits for sullage disposal. The pit may be 1-2 m deep, filled with rocks and it should be sized based on the volume of the greywater and the allowable infiltration rates for different soil types. The infiltration rates applied for greywater may be twice the values for toilet waste (presented in Franceys et al., 1992; Mara, 1996), as sullage infiltrates twice as fast as toilet waste (Mara, 1996).

In highly congested urban areas sullage disposal methods that rely on soil infiltration (as explained above) cannot be applied. In these cases, open drains can be used for conveyance of sullage, being either designed for this purpose or being storm water drains which are used by the people for emptying their greywater. They can be acceptable means of sullage disposal provided that they are designed and maintained in such a way that ponding of water does not occur in them (Franceys et al., 1992). Ponded waters can be formed when the drains cross section is too big for the amount of the sullage, for they are too flat or they are blocked by solid refuse deposited in them (Franceys et al., 1992). The main hazard caused by sullage is with regard to mosquitoes which breed in polluted ponded water and may have the risk of *Bancroftianfilariasis* (Mara, 1996, Franceys et al., 1992).

Avoiding the formation of ponded water in drain channels is not easy. In the construction phase, a circular channel made in the cross section of the main channel allows for faster movement of sullage in the channel during dry weather periods (Mara, 1996; Franceys et al., 1992). Another intervention is using grilles on top of the channels to avoid entrance of the solid refuses in to channel (Franceys et al., 1992). Maintenance of drain channels is of important concern and should be managed properly to ensure that the health risks associated with sullage disposal through drain channels is minimized.

Another way of sullage disposal is its collection in a septic tank (together or separate from blackwater) from where it can either percolate into the soil or be transferred to the sewer network (van Buuren, 2010). It may also be directly transferred to the sewer system if such a system exists.

If under the present situation there is no in-house piped water supply and the system that is going to be designed can only cope with the present wastewater flows, then there should be provisions for future larger wastewater flows that may be produced if in-house piped water supply is going to be available. The larger the piped water supply coverage is and the larger the delivered flows are, the more need will rise for such provisions.

In this thesis, the probability of non-exceedence of wastewater flows from maximum design flows is used for evaluating the facilities with regard to the criterion: *compatibility with population growth and/or prospective water supply coverage*. The more the wastewater flows increase in the future, the less compatible the system is likely to be with future conditions. The compatibility may be defined as:

$$\begin{aligned}&Compatibility\ with\ population\ growth\ and\ future\ water\ supply\ coverage\\&=\ probability\ of\ nonexceedence\ of\ wastewater\ flows\ from\ maximum\ design\ flows\end{aligned}$$

Equation 13

The probability of non-exceedence of wastewater flows is determined by piped water supply coverage, the delivered flows and the population growth. It may be quantified using a cumulative probability distribution function as:

$$F(X) = \int_0^X f(x)dx \qquad \text{Equation 14}$$

in which $F(X)$ is the cumulative probability distribution function that represents the probability that a random variable (in this case the future wastewater flows) will be equal to or below the value X (in this case the maximum design flows), and $f(x)$ is the probability density function of the same variable.

7.1.1. Quantification of future in-house piped water supply coverage and population growth

To predict the in-house piped water supply coverage in the future, the coverage trend as it has occurred during the past years shall be available. Such data is often accessible and based on that the coverage percentage vs. time can be derived by regression.

It should be noted that in derivation of coverage vs. time relations, the time series data to be used shall be collected for the specific socio-economic region type where the study is being undertaken. Using the general coverage trends in a big scale (like for the whole country) shall be avoided as the values may be misleading. In a survey done in Kazakhstan, the percentage of the households with water connection in urban areas varied between 60% to 98%, while in the rural areas the values mainly ranged between 0 to 25% (O'Hara et al., 2008). Coverage values with huge differences between the urban and rural areas (see Figure 27) have been also reported for Ethiopia for instance (Kumie and Ali, 2005).

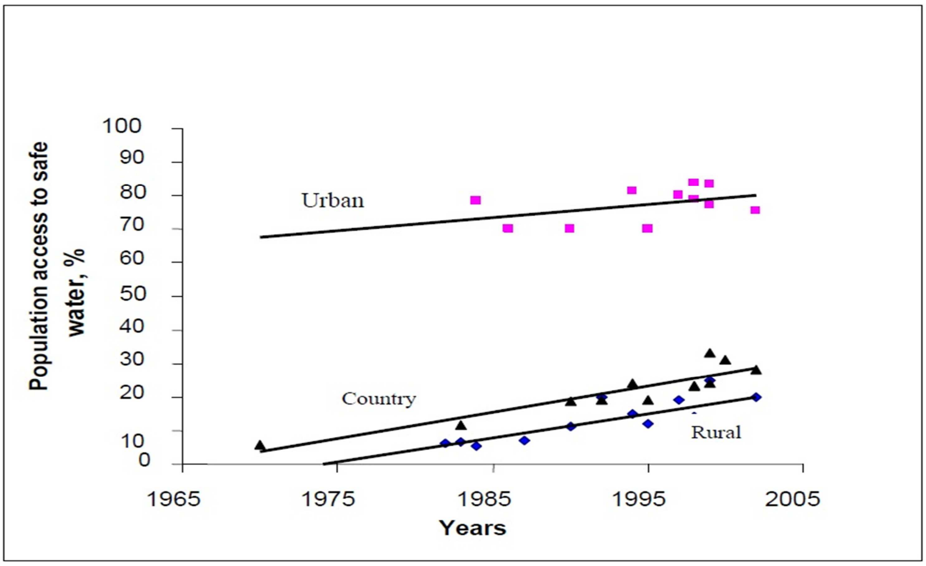


Figure 27: Trends of drinking water coverage in Ethiopia from 1970 to 2002 (Adapted from Kumie and Ali, 2005)

Letema (2012) goes even further in his observation on the differences among various socio-economical areas with regard to service coverage. In a study in 2 urban areas, Kisumu in Kenya and Kampala in Uganda, he reports large differences in coverage among high and medium-income areas, industrial zones and low-income and informal settlements; all located within the same cities. This shows that the coverage trends vary significantly not only between rural and urban settings, but also with regard to the specific socio-economic status of a region within an urban or rural setting.

Once the piped water supply coverage trends are derived for the specific region type for which the evaluation is going to be performed, the coverage value for the future shall be predicted. This 'future' time shall be determined by the decision makers. In the best case, the design life of the sanitation facilities may be used as the end point up to which the facilities are expected to be functioning appropriately.

For the selected time in the future, the coverage trends shall be extrapolated from the past data to derive the future estimates. This extrapolation shall be done using experts judgments. These experts shall be from the authorities and organizations who are responsible for planning and decision-making regarding water supply projects. The extrapolating may be misleading if solely the past years trend is used. There is a requirement for other indicators as well that can facilitate the extrapolation from the past years trend. The indicators for predicting the future values of piped water supply coverage could be: the past years trend, the development plans made by the authorities, the budget allocations for water supply projects and the priority ranking of the region with regard to implementation of water supply projects. If a clear in-house water supply plan has been developed for a region and the financial resources have been made available for that, then the coverage trend may even grow with an increased slope in comparison with the past years trends. In Swaziland for instance, it has been indicated that with an increase in annual investment in water supply projects in 2004, the water supply coverage increased drastically (Mwendera, 2006; see Figure 28).

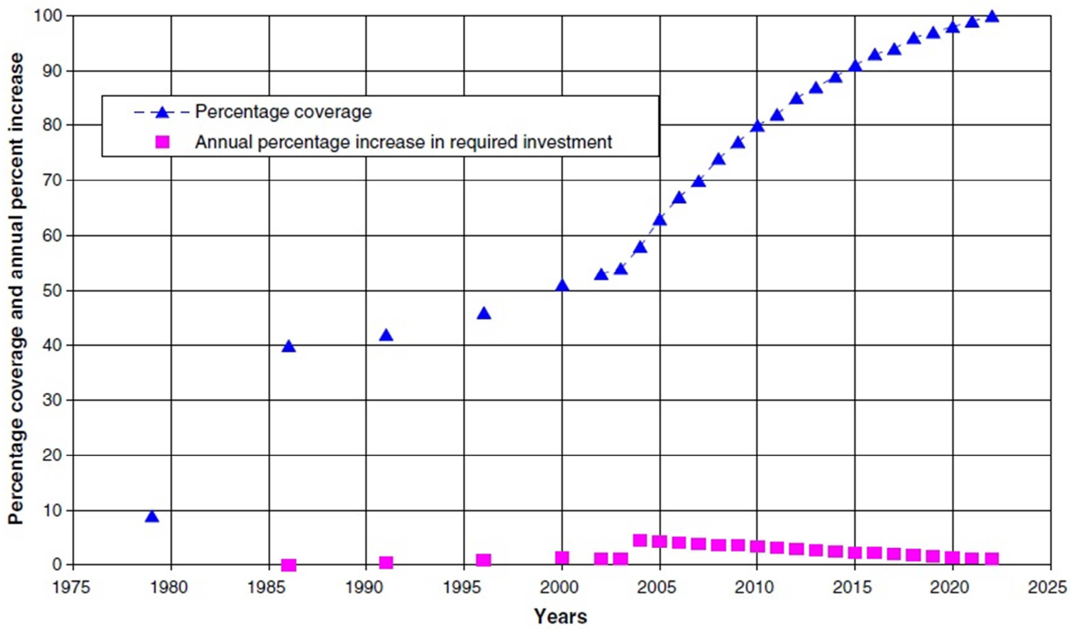


Figure 28: Percentage of water coverage and percentage of increase in annual investments for Swaziland (Adapted from Mwendera, 2006). The points for the years following 2005 are predicted estimates.

Once the future coverage is predicted, the amount of the water that is going to be delivered should be estimated. If the development plans already exist for the study area, the values for the water supply delivery are in most cases predicted in the plans. The delivered capacities will be determined by the intake capacity from the water source, the treatment capacity and the water transfer capacity. However, the water supply values will be more reliable only if the budget that is required for such development projects is already ensured. Otherwise, experts' opinion and their prediction for the prospective water supply capacities in the region shall be used. These experts could be the water authorities at local and/or national level or any other person or organization who is involved in planning or execution of water supply projects in the study area.

To estimate the amount of the waste flows that will be produced in the future as a result of population growth, the prospective population must be predicted. For any arbitrary time in the future the population can be estimated knowing the average growth rates and the present population. Using the exponential growth, the future populations can be determined at any point of time by:

$$N = N_0 e^{rt} \qquad \text{Equation 15}$$

with N being the prospective population at time t, N_0 being the present population and r being the average rate of population growth.

Once the future population is estimated, the waste flows could be estimated knowing the toilet type (dry or pour-flush or cistern-flush) and the amounts of the liquid waste that is produced in each of these facilities. In dry latrines for instance, the volume of the liquid waste is slightly higher than the volume of the urine that is produced by the users (e.g. about 1 liter per person per day in a tropical climate with vegetarian diet; Franceys et al.; 1992). In wet toilets, the main part of the liquid waste is produced from the water that is used for flushing (about 9 liter per person per day in pour-flush toilets and about 40 liter per person per day in cistern-flush toilets; van Buuren, 2010).

The predictions for water supply coverage, volumes to be delivered and population growth are uncertain and therefore the wastewater flows that exceed the system design are uncertain. The coverage may increase in the future due to budget allocation from other resources that are not present currently. The coverage can also be less than predictions due to budget shortage or technical prohibitions. The volumes to be delivered can also deviate from the predictions due to technical or financial reasons. Nevertheless, in lack of certain data, educated predictions are the only solution and shall be used for evaluation purposes. At the same time, if more insight is required into the impact of different predictions (of coverage, volume delivered and population) on the produced wastewater flows, this can be done by changing the coverage and the water supply volumes within the most probable ranges and assigning the probability distribution to the prospective wastewater flows. The range within which the wastewater flows varies, indicates the uncertainty range that exists in the results.

7.1.2. Risk of groundwater microbial pollution as a result of increased flows

When a sanitation facility that relies on soil infiltration is to be designed, the soil type determines the permissible hydraulic loading rates that should be applied. The recommended hydraulic loading rates are presented in various literature (e.g. Franceys et al., 1992; Mara, 1996; Howard et al., 2006) for different soil types and they indicate the maximum rates that shall be maintained in order to facilitate soil infiltration of the leachate and also to avoid excess risk of groundwater pollution. In high hydraulic loading rates, the risk of pathogens reaching the groundwater table increases because in a significantly wetted unsaturated zone the travel times decrease and therefore the attenuation of pathogens is reduced (ARGOSS, 2001). However, in areas where the groundwater pollution is of no concern, higher hydraulic loading rates may be applied if the permeability of the soil allows (Franceys et al., 1992).

Once the maximum hydraulic loading rates are chosen based on site conditions, the infiltration area can be calculated knowing the flows that are introduced into the soil (see equation 16).

$$Infiltration\ area = \frac{flow\ of\ the\ wastes}{hydraulic\ loading\ rate} \quad \text{Equation 16}$$

The flow of the wastes is determined from the number of the people who use the facility and the volume of the liquid waste that is produced by them (1 litre per person per day for dry latrines and about 9 litre per person per day for pour-flush toilets).

Although a sanitation facility may be designed to serve a specific number of people (and thus a specific number of waste flow resulting in a specific infiltration area), but the future increase in the population may change the amount of the flows and consequently the required infiltration area. This is of special concern in public sanitation facilities that are implemented in a large scale in slum settlements of low-income countries (Letema, 2012). Such facilities may be overloaded with rapid growth in the population, that results in an increase in flows of human wastes. In that case the hydraulic loading rates increase. If the soil is coarse type, the groundwater pollution risk increases and if it is a compact soil, the soil passage may be prohibited resulting in overflowing of the facilities if they are not de-sludged on a more frequent basis.

Therefore, public sanitation facilities that rely on soil infiltration shall be evaluated with regard to their risk of polluting the groundwater as a result of population growth.

With the prospective liquid waste flows that are going to be produced by the grown population, the new hydraulic loading rates could be calculated (using equation 16), assuming that the infiltration area is not increased.

Knowing the future increased hydraulic loading rates, the travel times in the sub-surface from the sanitation facility to the water supply wells can be estimated again using the procedure as explained in section 4.1. If using W*h*AEM program to estimate the travel times in the sub-surface, the recharge rate from the sanitation facilities shall be increased in the future model, while other input parameters may remain the same assuming that the environmental parameters and well abstraction rate remain the same in the future; otherwise these parameters shall also be changed according to the prospective situation. The probability of groundwater pollution from the increased loading rates can then be estimated in the same way as it is done for the newly designed systems (see section 4.1).

7.1.3. Measures to increase the compatibility of the sanitation facilities with the population growth and prospective water supply coverage

Although population growth is a big concern in low-income countries and is considered to be strongly contributing to escalation of many problems in these countries, measures to control this growth rate are out of the scope of this thesis. Instead, measures to increase the compatibility of sanitation facilities with the growing populations will be presented here.

If the predictions for in-house piped water supply coverage in a region result in high coverage values, then it should be realized that the dry sanitation facilities will be highly vulnerable to such changes. If big changes are expected within a short time, it may be advisable to construct pour-flush toilet facilities without direct soil infiltration (with septic tanks for instance). Pour-flush toilets can be easily modified and made compatible with in-house piped water supply.

With regard to sanitation facilities that rely on soil infiltration, minimizing the waste flows will keep the hydraulic loading rates low, assuming a fixed infiltration area (see equation 16). This can be done by implementing dry toilets rather than flush toilets as public facilities, in areas where the population growth is expected to lead to high hydraulic loading rates and consequently soil and groundwater pollution.

Increasing the infiltration area is also another measure to decrease the hydraulic loading rates resulting from the growing population. Constructing soakage trenches instead of soakage pits will increase the infiltration area. Moreover, as these trenches will be built in shallower depths compared to the pits, the groundwater pollution risk will be lowered. With shallower depths, the distance to the groundwater table or to the well inlet will be increased and more attenuation of pathogens in the sub-surface may be achieved (Howard et al., 2006). The drawback however, is that soakage trenches require a larger area to be constructed and the construction costs will increase drastically.

To protect the groundwater from pollution as a result of increasing population, measures to decrease the risks of groundwater pollution could also be taken in to consideration. These measures have been previously presented in section 4.1.4.

While water supply projects may attract investments, the available financial resources for upgrading the toilet facilities to flush toilets may not be available. The global public mind set in the past many years has been formed by strongly linking the water supply to sanitation and hygiene, paying less attention to waste-disposal facilities. There is a lot of political interest and enthusiasm among donors with regard to investing in water supply projects, while implementing toilet facilities is not eagerly addressed. The new sanitary revolution, as defined by Black and Fawcett (2008), requires de-linking of water supply from sanitation in the public and official mind set.

In absence of the required resources that lead to construction of sanitation facilities that are more compatible with future advances in water supply, training of the users with regard to correct usage of dry sanitation facilities, when in-house piped-water supply is made available, shall be considered. The extent of success of these training practices is questionable though, as already addressed in section 6.2.

8. Case Study: Sanitation for the Unplanned Peri-urban Settlement of Nyalenda in Kisumu City, Kenya

Kisumu is a port city lying along the shores of the fresh water Lake Victoria in western Kenya. It is the third largest city in Kenya, with a population of more than 900,000 (KNBS, 2009 census). The population growth rate is about 5% annually (Tito Iro Ong'Or and Long-Cang, 2007) which is far beyond the previous predictions of about 2% per annum that was based on the 1999 census (NCAPD, 2005).

Kisumu has a topography ranging from 800 to 1900 m above sea level, a temperate climate with annual mean temperatures between 18 to 29^{o}C, and a mean annual rainfall of about 1300 mm (Ministry of Agriculture, Irrigation and Drainage, cited in Tito Iro Ong'Or and Long-Cang, 2007).

The most common type of sanitation in Kisumu is pit latrine due to lack of sufficient water supply (Letema 2012; Tito Iro Ong'Or and Long-Cang, 2007; UN-Habitat, 2005). Pour-flush toilets connected to septic tanks and conventional sewerage systems are the next common modes of sanitation in Kisumu, while eco-san facilities and bio-latrines are also available but in limited use (Letema, 2012).

The Municipal Council of Kisumu has established a water company under the name of Kisumu Water and Sewage Company (KISWASCO), which became operational in 2003 (Wagah et al., 2010). KIWASCO is responsible for water supply and collection, treatment and disposal of sewerage in a safe manner (Wagah et al., 2010).

Kisumu is divided into different settlement areas including: Milimani, Okore, Migosi, Manyatta, Nyalenda, Nyamasaria and Mamboleo (see Figure 29). Nyalenda is an unplanned settlement with about 5000 households and a mean family size of about 5 people (Wagah et al., 2010). It is located in a flood-prone area with permanent or seasonal swamps covering the settlement area (Tito Iro Ong'Or and Long-Cang, 2007; UN-Habitat, 2005). Contrary to the belief that water companies are reluctant to provide water to informal settlements due to negligible financial return, Nyalenda settlement is served with treated water from KISWASCO, mainly through many water kiosks in the area, and also through in-house piped connections or yard taps that both together serve about 43% of the population (Wagah et al., 2010). Only a small portion of the population buys water from water vendors or use water from the wells (Wagah et al., 2010). Nyalenda enjoys one of the longest hours of water supply compared to most other areas in Kisumu, with the majority of population having access to 18-24 hours water service; however, the mean water consumption remains at about 22 litres per person per day, due to financial limitations of the households (Wagah et al., 2010).

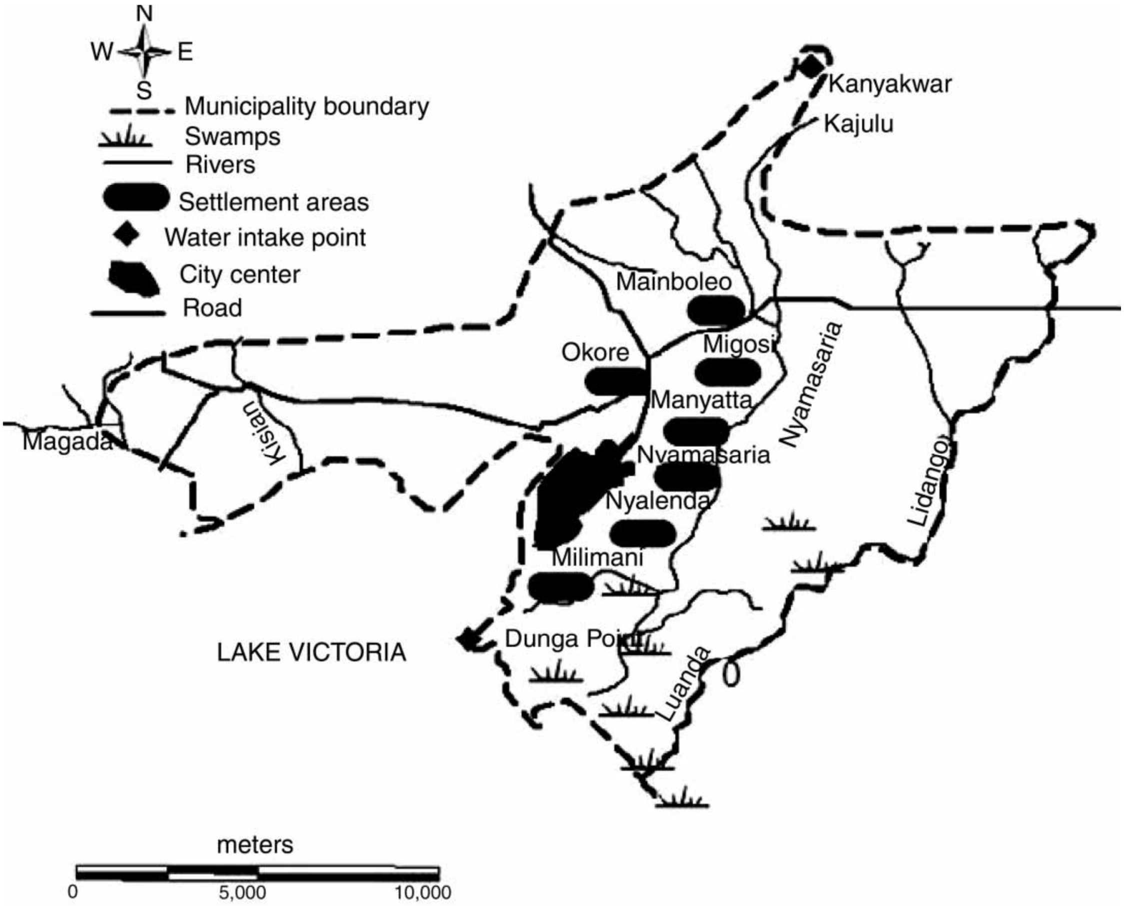


Figure 29: Location map of Kisumu. Adapted from Tito Iro Ong'Or and Long-Cang (2007)

Nyalenda settlement is dismally sewered, with half of the population relying on shared latrines, 40% of the population relying on private latrines and 10% of the population having septic tanks that receive flows from pour-flush toilets (Letema, 2012). Due to high water tables shallow pits are dug in the area (Letema, 2012). Septic tanks largely contribute to groundwater pollution in the area (UN-Habitat, 2005) due to the large hydraulic loading rate they impose to the soil. On the other hand, existence of black cotton soil in parts of Nyalenda, prohibits construction of toilets that rely on soil infiltration (UN-Habitat, 2005) due to the low permeability of this soil type. Open defecation and use of plastic bags for disposal of excreta is practiced in those regions (UN-Habitat, 2005). Five eco-san facilities have been also implemented in Nylenda in 2011, by consortium of a few NGOs, but not becoming fully operational yet as users' sensitization is on-going (Letema, 2012). A bio-latrine has also been built in Nyalenda for a primary school, but the bio-gas utilization from this facility is postponed to the time when the relocation of the kitchen to 60 m distance of the digester has been accomplished (Letema, 2012).

Nyalenda waste stabilization ponds were developed in 1976-1977 to take care of the future wastewater flows from Kisumu eastern catchment (Letema, 2012). They receive wastewater from the main sewer line of Kibos-Mamboleo, plus the septage from septic tanks in the area;

however, they work with only 30% of their design load and therefore are under-utilized (Letema, 2012). The effluent is being used for irrigation of vegetables, but the hygiene quality of the recycled water is unknown (Letema, 2012).

8.1. Implementation of the screening and the probabilistic evaluation for new sanitation options in Nyalenda

Nyalenda unplanned slum settlement in Kisumu, Kenya, is chosen to serve as an example for performing the decision-making approach as developed in this thesis. The data that serve as the basis for this evaluation is presented in other works on this area (e.g. Letema, 2012, Wagah et al., 2010; Tito Iro Ong'Or and Long-Cang, 2007; UN-Habitat, 2005) and is neither collected nor validated by the author of this thesis. Moreover, there is a lot of data lacking from the site that is required for the probabilistic evaluation of sanitation options. In those cases, the evaluation will be performed based on some rough assumptions. Therefore, the results that are derived based on this data (and lack of data) cannot be completely justified; however, they can be used as an indicative example for the method of evaluation that is developed in this work.

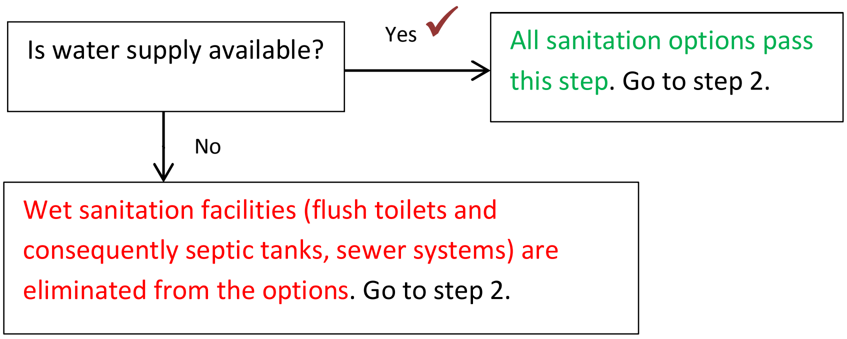
Problem definition:

Assume that shared sanitation facilities are going to be implemented in one part of Nyalenda settlement, where there is black cotton soil and the groundwater table is high. Water supply is available in the area through water kiosks and yard taps with on average 18 hours per day service. The available sanitation options include the ones that already exist in the area, i.e. pit latrines with direct soil infiltration of leachate, pour-flush toilets connected to septic tanks (with or without soil infiltration) and eco-san facilities (double-vault). The locations for the prospective toilets will be the same for all options and independent of the sanitation type.

8.1.1. Stage 1: Screening of the options

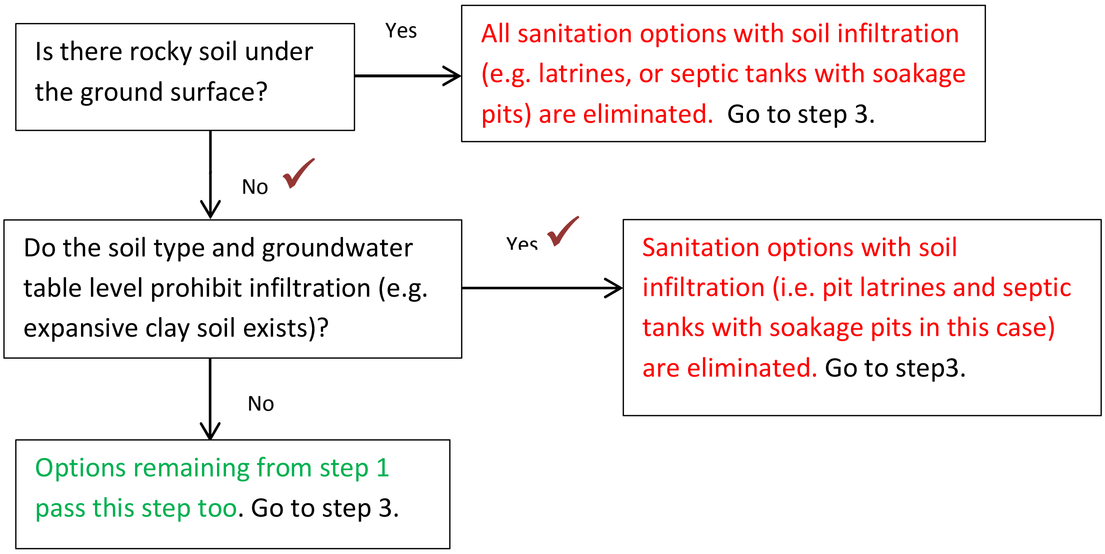
In the first stage, the available options shall be screened based on the screening algorithm (presented in section 3.2) to filter out the options that cannot be implemented and will not function under the existing situation. It should be noted that in every stage of the decision-making process, the whole sanitation chain shall be taken into account and not only the toilet facilities for instance.

Step 1: For all sanitation options



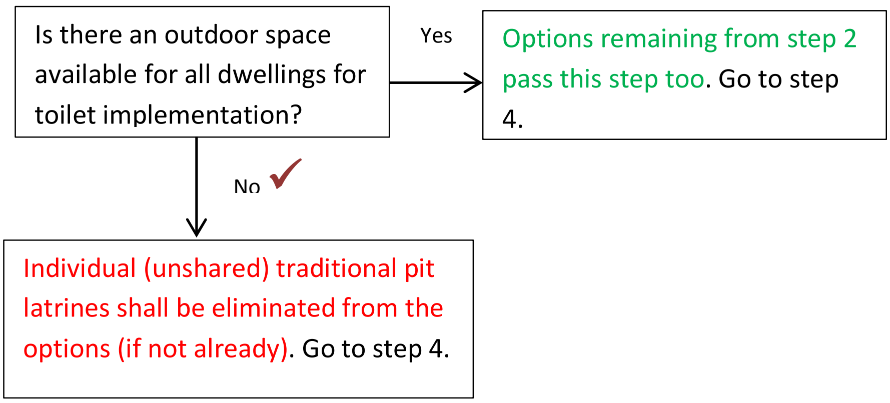
The area under study is served with water kiosks and yard taps, therefore, all available sanitation options may pass this step.

Step 2: For the remaining sanitation options from step 1



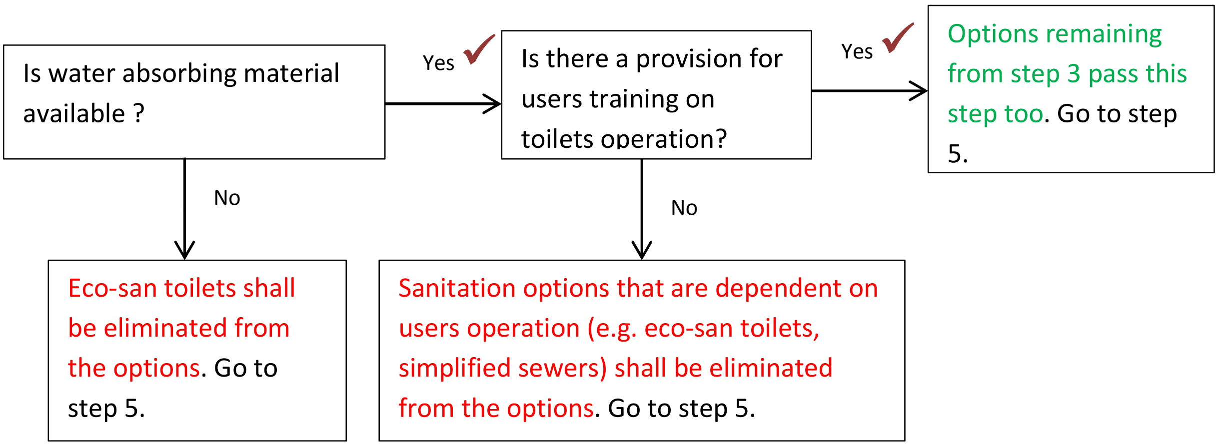
The soil type (black cotton soil) does not facilitate infiltration of high hydraulic loading rates from shared septic tanks supernatant, especially with increased usage due to rapid population growth in the area. So the option of septic tanks with soil infiltration shall be eliminated. However, settled sewers connected to septic tanks could be an alternative option, with their flow going to Nyalenda waste stabilization ponds which are currently under-loaded. On the other hand, the groundwater table level prohibits construction of shared pit latrines as shared latrines required more storage capacity and consequently deeper digging of the pits. High groundwater table prohibits deep digging of the pits and does not facilitate soil infiltration either.

Step 3: For the remaining sanitation options from step 2



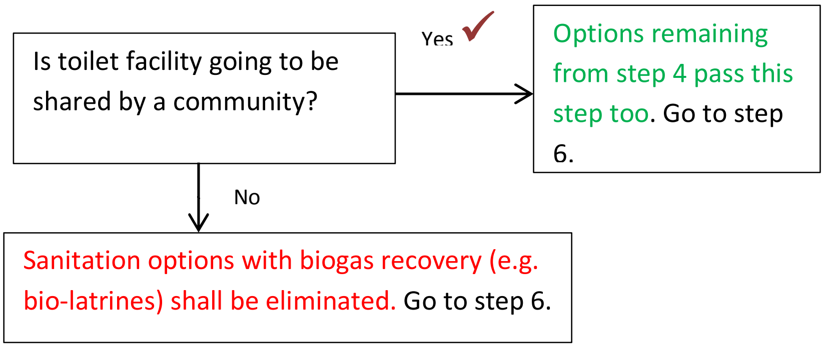
As only shared facilities are already under consideration for this case, this step does not have an impact on the options that shall pass through this step.

Step 4: For the remaining sanitation options from step 3

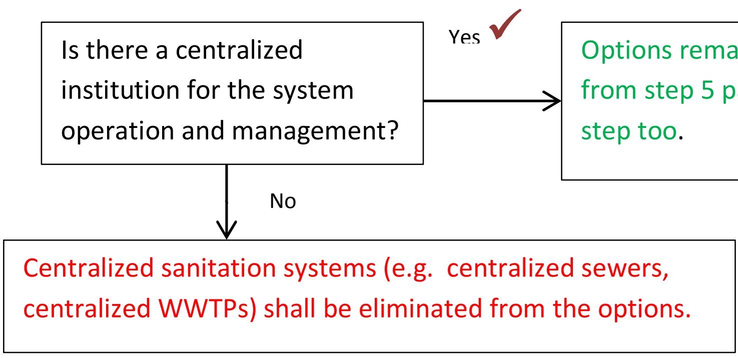


As eco-san facilities (that work with water absorbing material) are already implemented in Nyalenda, it is assumed that water absorbing material are available. It is also mentioned by Letema (2012) that user's training have been performed with respect to previous eco-san facilities in Nyalenda.

Step 5: For the remaining sanitation options from step 4



Step 6: For the remaining sanitation options from step 5



KISWASCO is a centralized institution that is already established by the Municipal Council of Kisumu, and takes care of waste collection, transfer and treatment in the city.

The remaining options out of the screening stage are pour-flush toilets connected to septic tanks and settled sewers, plus eco-san facilities (double-vault). These options may enter the probabilistic evaluation in which they will be assessed based on the evaluation criteria.

8.1.2. Stage 2: Probabilistic evaluation of the remaining sanitation options

The probabilistic evaluation of eco-san facilities (double-vault) and pour-flush toilets connected to septic tanks and settled sewers will be carried in this section with regard to the evaluation criteria (see section 3.3).

Assessment criterion: Exposure to health hazards:

Indicator: Groundwater microbial pollution protection

Without any local wells in the area and considering the fact that both sanitation options don't rely on soil infiltration, then the evaluation of groundwater pollution risk may be skipped.

Indicator: Exposure of users to faecal matter

As explained in section 4.2, up to now no published evidence of difference among sanitation options with regard to health risks arising from using them could be found. Therefore, both eco-san facilities and pour-flush toilets will be evaluated equally with respect to this indicator.

Indicator: Exposure to faecal matter during waste collection

Faecal sludge shall be emptied both from septic tanks and eco-san facilities. The frequency of faecal sludge collection is assumed to be similar for both options. However, the sludge from septic tanks will be retained in a wet environment that favours pathogens survival (Franceys et al., 1992; Feachem et al. cited in Jenkins, 2005), while the sludge from eco-san facilities can be retained in the first vault (while the second vault is in use) for several months. Due to addition of water absorbing material to the faecal matter in eco-san facilities, the moisture is reduced and the pH increases. These facilitate the reduction of pathogens, especially *E.coli* and *Ascaris* eggs in the faecal sludge from eco-san facilities (Chaggu, 2004).

Although emptying of faecal sludge from septic tanks is often mechanized and emptying of faecal sludge from eco-san facilities is often manual, but as explained in section 4.3, causalities that occur in mechanical emptying and the high frequency of the emptying practice for waste workers increase the total contact times for them anyhow. As it was discussed in section 4.3.4, for the same contact times, the health risk caused by exposure to faecal sludge by workers increases when there is less degree of pathogenic inactivation achieved in faecal sludge (see Figure 14). It may therefore be concluded that without protective measures for workers, the health risks arising from septic tanks is likely to be larger than the ones for eco-san facilities with double vaults. However, because the exact dose of specific pathogens and the exact contact time are unknown for both types of facilities, quantified evaluation is not possible in this case.

Final result on the criterion

The final result for evaluation of the options against the criterion of *exposure to health hazards* is dependent on the evaluation score from the last indicator, i.e. exposure during waste collection. This is because previous indicators for this criterion (groundwater pollution and users' exposure) result in similar evaluation for both sanitation options as explained before. Although the exact health risks caused by de-sludging of the facilities in both options are unknown, it can be concluded that septic tanks are likely to impose greater health risks to the waste workers, in comparison to eco-san facilities with double vault. However, the overall impact of this risk is reduced by the small percentage of the population who is at risk due to this practice. Risk mitigation measures related to de-sludging activities can also decrease the health risks further (see section 4.3.5).

As a result, eco-san facilities will be evaluated higher with respect to the criterion of exposure to health hazards.

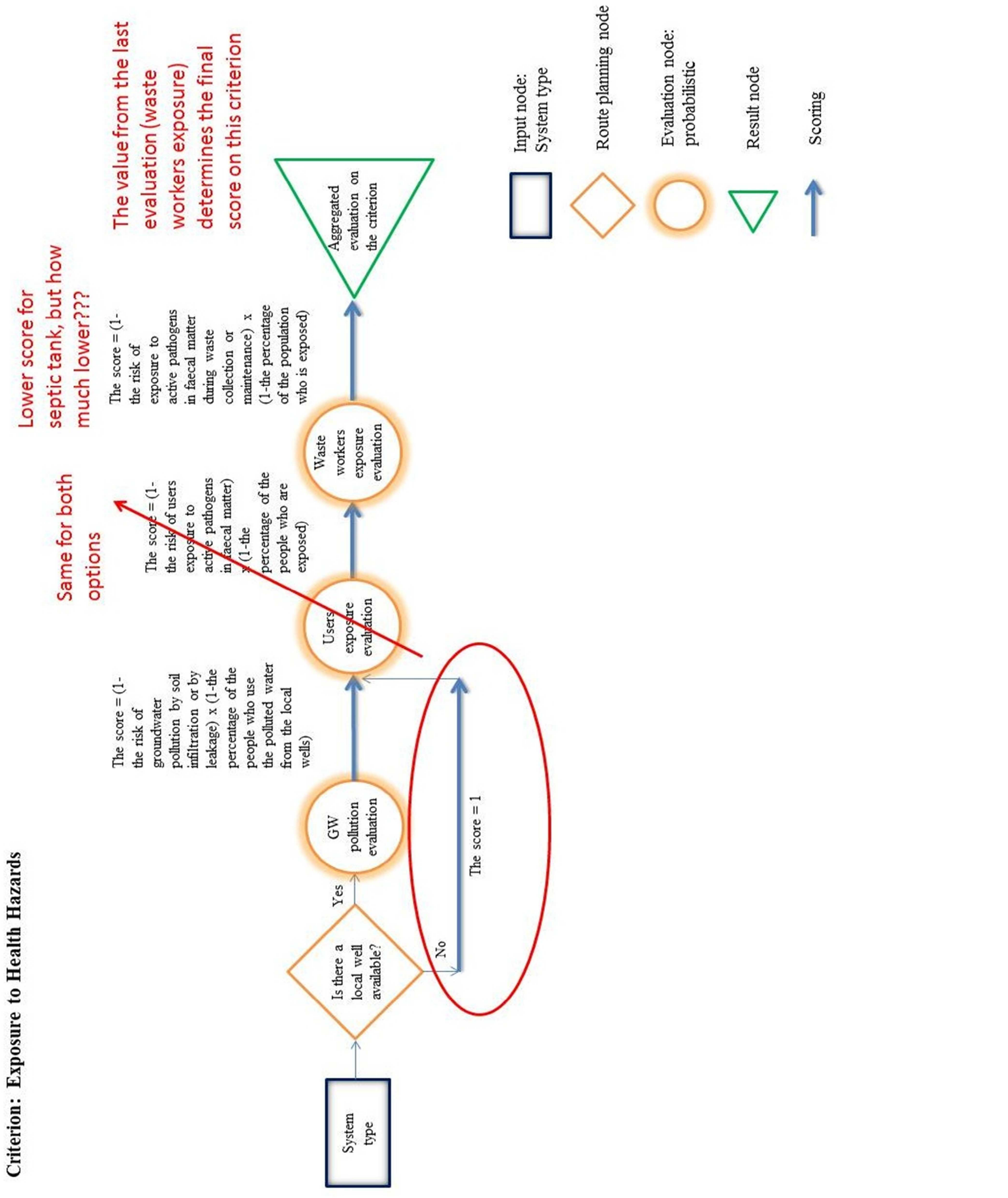


Figure 30: An example evaluation of pour-flush toilets with septic tanks and settled sewers versus eco-san facilities with respect to exposure to health hazards criterion, for an example area in Nyalenda settlement, Kisumu, Kenya

Assessment criterion: Accessibility

Indicator: Users' accessibility

Both types of facilities are going to be implemented in the same location and therefore there is no difference between the two options with regard to users' accessibility.

Indicator: Reuse centres accessibility

For pour-flush toilets with septic tanks this evaluation is not applicable. Although faecal sludge from septic tanks may also be reused after further treatment, but development of these facilities is not meant with direct reuse and recycling provisions. Thus, reuse centres accessibility is not of great concern in selection of this sanitation option, especially considering the fact that sludge treatment is another step before reuse and sludge from septic tanks is not going to be reused directly. If reuse occurs, it is not the goal of the system but rather a benefit. This benefit can impose its impact on the cost evaluation of the system where the operational or investment costs may be compensated by the income from reuse products.

In contrast, eco-san facilities are developed based on reuse provisions. Therefore, an evaluation on reuse centres accessibility is crucial. There is no evidence in the available data that a link between toilets and reuse has been established in Kisumu. Experience from similar locations (e.g. Manyatta settlement in Kisumu) indicate that the link is missing and eco-san toilets were not utilized as they were aimed for and remained only as 'show cases' (Letema 2012).

Assuming that only 10% of the toilet products could be reused at the vicinity of toilets by the neighbouring community (e.g. in their own gardens), the score of eco-san facilities with respect to this indicator will be 0.1.

Final result on the criterion

The final result on the evaluation criterion of *Accessibility* results in a score that may be 10 times bigger for pour-flush toilets +septic tanks, if the eco-san toilets does not fill the gap between production and reuse as they are aimed for, and only 10% of their products would be reusable in practice. The more products reach the reuse centres from eco-san facilities, the higher its score would go and it would be competitive with the other option with respect to the accessibility criterion.

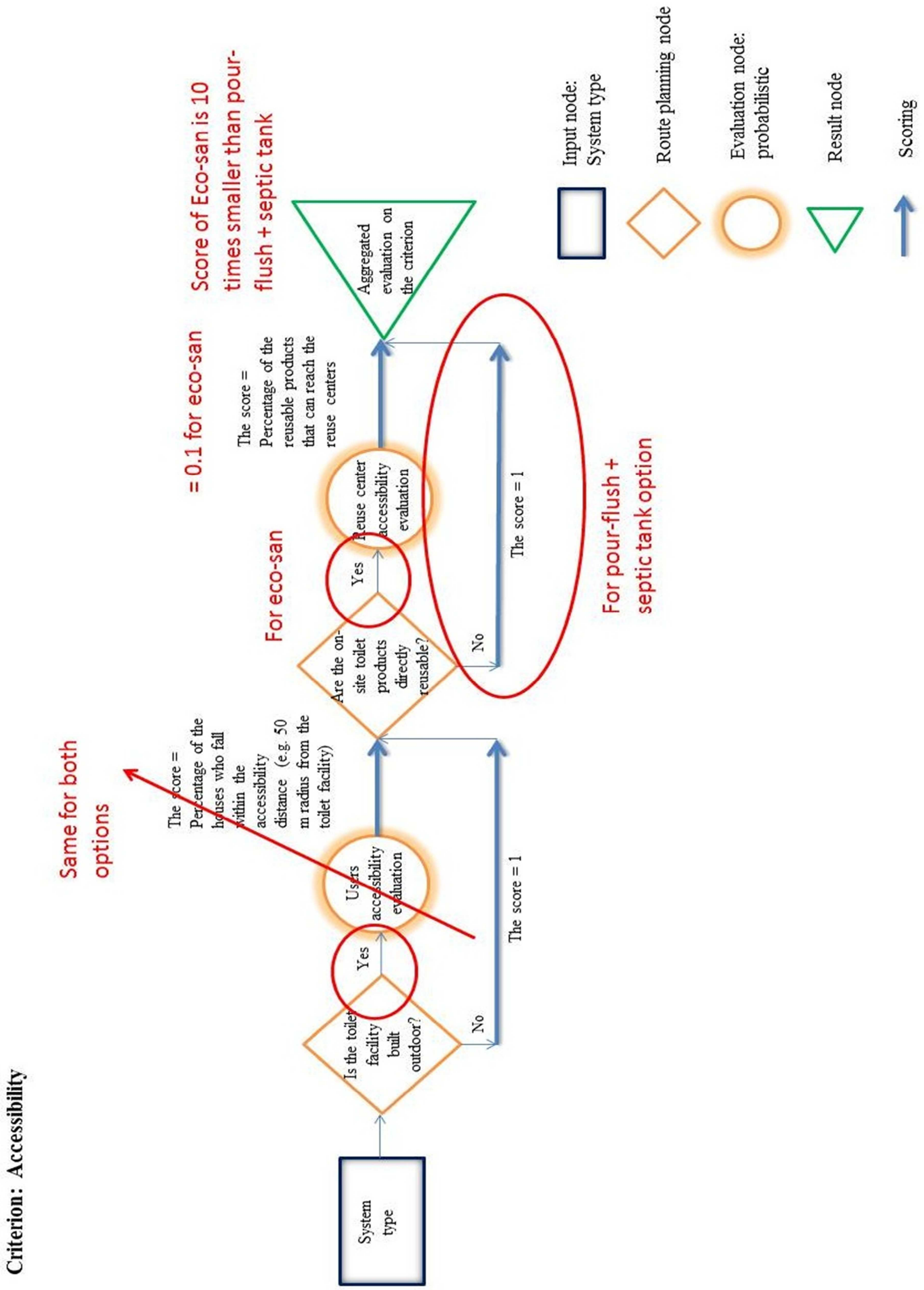


Figure 31: An example evaluation of pour-flush toilets with septic tanks and settled sewers versus eco-san facilities with respect to accessibility criterion, for an example area in Nyalenda settlement, Kisumu, Kenya

Assessment criterion: Reliability

Indicator: Water supply reliability

Eco-san option may skip this assessment step as it is not dependent on water supply. Pour-flush toilets with septic tanks and settled sewers are dependent on water supply and therefore affected by water supply reliability.

As stated in the case definition, the water supply is available in this part of Nyalenda through water kiosks and yard taps for 18 hours per day on average. As the water cut is not a random event due to failure in system, but rather a routine with certain hours of occurrence, the reliability of water service may be quantified as:

$$Reliability\ of\ water\ service = \frac{Number\ of\ hours\ with\ water\ service}{total\ hours\ per\ day} = \frac{18}{24} = 0.75$$

Nevertheless, this reliability is the raw reliability score without any improving measures. Depending on storage capacity at the users side, the reliability value could be increased.

Indicator: Reliability of users' practices

Probability of incorrect usage of sanitation options is quantified by (see section 6.2.1):

$$Probability\ of\ incorrect\ usage = \frac{Number\ of\ incorrect\ practices\ that\ occur}{Total\ number\ of\ incorrect\ practices\ opportunities}$$

Incorrect practices for pour-flush facilities include the ones that make the surrounding areas stained by excreta and urine or the ones that cause blockage of the U-trap (putting bulking material in the facility for instance). The former is applicable to eco-san facilities as well, but they are even sensitive to other incorrect practices. Excreting in the urine hole or urinating in the excreta hole are examples of these incorrect practices.

There is a need for a monitoring program to examine the frequency of occurrence of incorrect practices by the users of facilities. Eco-san facilities are very new in Nyalenda and there is no data on their usage so far. So for this example, the data from socio-culturally similar locations may be applied. In Kisumu, another settlement with eco-san facilities is Manyatta, which turned out to be a failure case as the implemented toilets are not in use, one reason being that the users had access to another type of sanitation facility (VIP latrine) and preferred to use that (Letema, 2012). However, in Kampala, Uganda, there has been a project in which eco-san facilities were implemented and afterwards monitored and evaluated to determine if they fulfilled their objectives. This monitoring report (Carlesen et al., 2008) states that only 60% of the users of eco-san facilities used them correctly, even after training provisions. The report doesn't breakdown the incorrect practices, but still gives an overall idea of the probability of incorrect usage.

Assuming that the case of Kampala is going to be more or less similar to the case of Nyalenda settlement in Kisumu (which may be an inevitable assumption in lack of data from the exact location), the reliability of users' practices with eco-san facilities will be scored at 0.4. For pour-flush facilities, that their function is not highly sensitive to users' practices, the reliability may be scored as 0.9, assuming that 10% incorrect usage may occur with people staining the surrounding area with their wastes for instance.

Indicator: System maintainability

To assess the maintainability of both options, the O&M activities and requirements for these systems shall be specified. For the option of pour-flush toilet + septic tank + settled sewers the main O&M activities and requirements are presented in Table 6. The O&M requirements of the waste stabilization ponds are excluded here as these facilities already exist and the new requirements imposed to them as a result of implementation of this project in a small area is perhaps negligible.

Table 6: Main O&M activities and requirements for pour-flush toilets + septic tanks + settled sewers

Activity and Frequency		Materials	Equipment
Pour-flush toilet			
Daily	Cleaning	Water	Brush
Monthly	Inspection of the facility		
Occasionally	Unblocking the U-trap and the pipe	Water	Stick or plunger
	Repairing the structure and the pipes	Building material	Basic repair tools
Septic tank			
Every few years	Emptying the sludge from the tank	Water and fuel	Vacuum tanker or MAPET
Settled sewers			
Regularly	Inspection	Special tool	Special equipment
Occasionally	Repairing of the facilities and unblocking of the pipes	Special material	Special equipment

The O&M activities and requirements for eco-san facilities are presented in Table 7. Most of the activities are very similar and have similar requirements as for the other option. However, the requirements for settled sewers are, for the case of eco-san, replaced by supply of water absorbing material and more frequent cartage of faecal sludge and urine. This means a higher fuel consumption to maintain eco-san facilities as water absorbing material, faecal sludge and urine shall be transferred between supply and demand locations frequently. In addition to transportation costs, the cost of water absorbing material shall also be considered.

Table 7: Main O&M activities and requirements for eco-san facilities

<table>
<tr><th colspan="2">Activity and Frequency</th><th>Materials</th><th>Equipment</th></tr>
<tr><td>Daily</td><td>Cleaning</td><td>Water</td><td>Brush</td></tr>
<tr><td rowspan="2">Monthly</td><td>Supply of water absorbing material</td><td>Fuel, water absorbing material</td><td>Vehicle</td></tr>
<tr><td>Inspection of the facility</td><td></td><td></td></tr>
<tr><td rowspan="2">Occasionally</td><td>Unblocking the urinal</td><td>Water</td><td>Stick</td></tr>
<tr><td>Repairing the structure and the facility</td><td>Building material</td><td>Basic repair tools</td></tr>
<tr><td>Every few months</td><td>Emptying the sludge and the urine from the tank</td><td>Water and fuel</td><td>Vacuum tanker or MAPET</td></tr>
</table>

In order to compare the maintainability of both options quantitatively, the differences in the O&M requirements of both options shall be specifically quantified. These differences are :

- Supply of water absorbing material for eco-san facilities (fuel and water absorbing material requirement)
- More frequent cartage of faecal sludge and urine for eco-san facilities (fuel requirement)

vs.

- Inspection, repairing and unblocking of sewer system for the option of pour-flush + septic tank + settled sewers

The distances between the supply and demand locations (for water absorbing material, fecal sludge and urine) are not known in this example. The distances, in addition to the local fuel price, determine extra cartage costs for eco-san facilities. On the other hand, the local costs for O&M of settled sewers are unknown. Therefore, with this lack of data maintainability of the two options can be compared quantitatively but it may be assumed that the values would be close to each other as both systems have some requirements that the other system does not have. Therefore, both systems may be evaluated almost equally with regard to the maintainability assessment.

Indicator: Proneness to flooding

Both systems are going to be implemented in the same locations. The construction level of both systems is also the same. Therefore, both systems would be evaluated equally with respect to proneness to flooding.

Final result on the criterion

With the available information and the assumptions made for the assessment of this criterion, eco-san facilities will be scored about 1.7 times lower compared to pour-flush + septic tank option, mainly due to its sensitivity to reliability of users' practices and it's low score on this indicator.

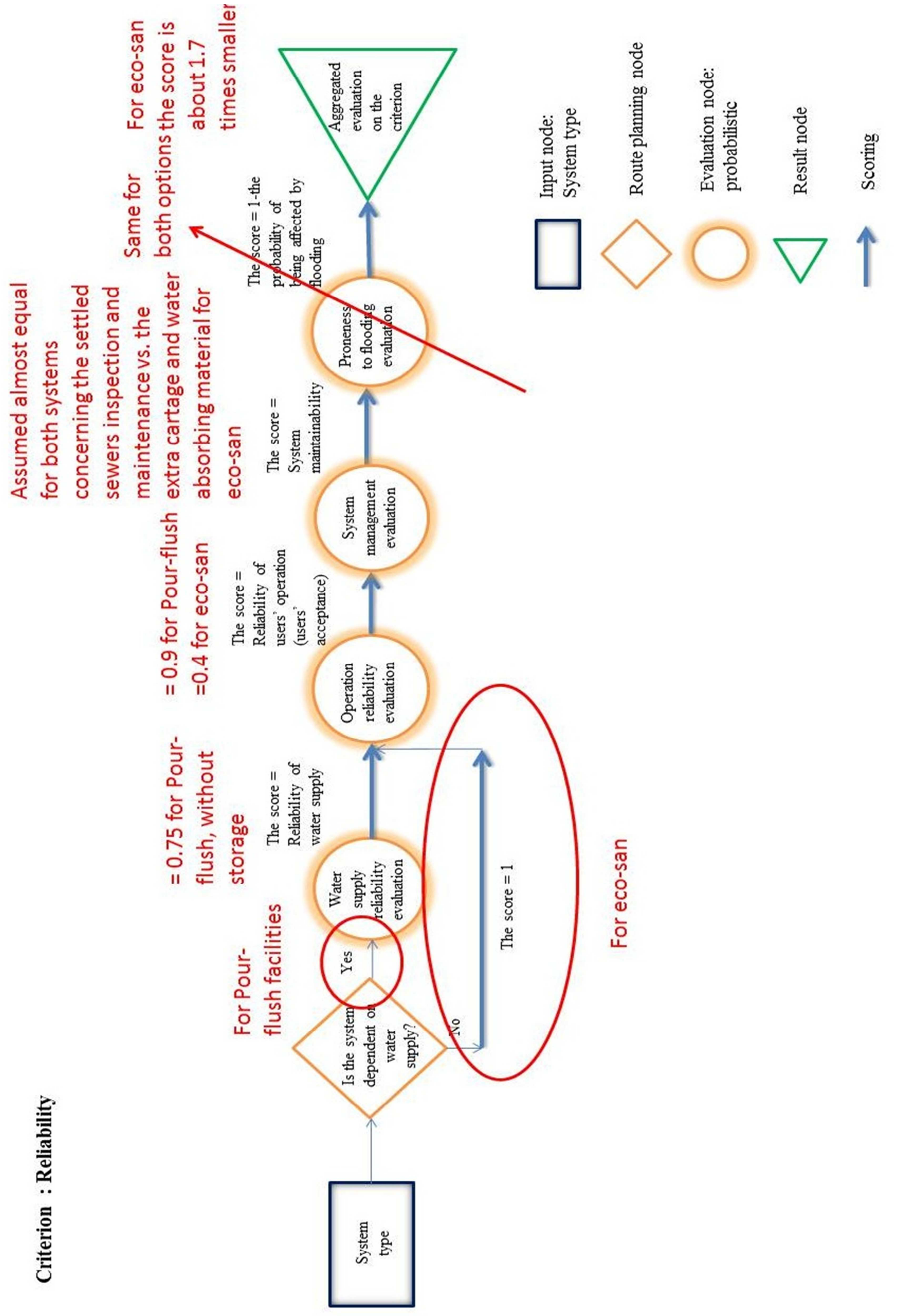


Figure 32: An example evaluation of pour-flush toilets with septic tanks and settled sewers versus eco-san facilities with respect to reliability criterion, for an example area in Nyalenda settlement, Kisumu, Kenya

Assessment criterion: Sustainability

Indicator: Compatibility with population growth and prospective water supply coverage

Population growth of about 5% per annum in Kisumu is relatively large and should be taken into consideration when designing the sanitation facilities for this area. For both of the sanitation options in this example, the main impact of the population growth on the systems would be the increased frequency for emptying and de-sludging of the facilities (i.e. eco-san containers and septic tanks). If both systems are going to be built with the same design loads and capacity, then the impact of the population growth on both systems will be equal.

With respect to water supply coverage, water kiosks and yard taps have already been implemented in the area and connection to in-house water supply is less likely to occur in the near future due to the socio-economic structure of this region. Low-income unplanned settlement area in Nyalenda is not likely to be a target location for in-house water supply coverage and the users are also less likely to be able to meet the cost of increased water consumption. Wagah et al. (2010) state that due to these financial limitations of the households, in spite of availability of water, the water consumption in the area has remained low (about 22 litre per person per day).

Thus, in absence of access to more information that indicate the future water supply coverage plans in Nyalenda, it may be rational to assume that the water service levels will not be considerably increased in the near future in this area.

Therefore, with the above justifications and assumptions, both sanitation options will be graded equally with regard to this indicator.

The risk of groundwater pollution as a result of population growth is not applicable to the sanitation options in this example as they don’t rely on soil infiltration and no local well is available in the vicinity of the sanitation facilities either.

Final result on the criterion

With the available information and the mentioned assumptions, both options are evaluated to be equal with regard to sustainability criterion.

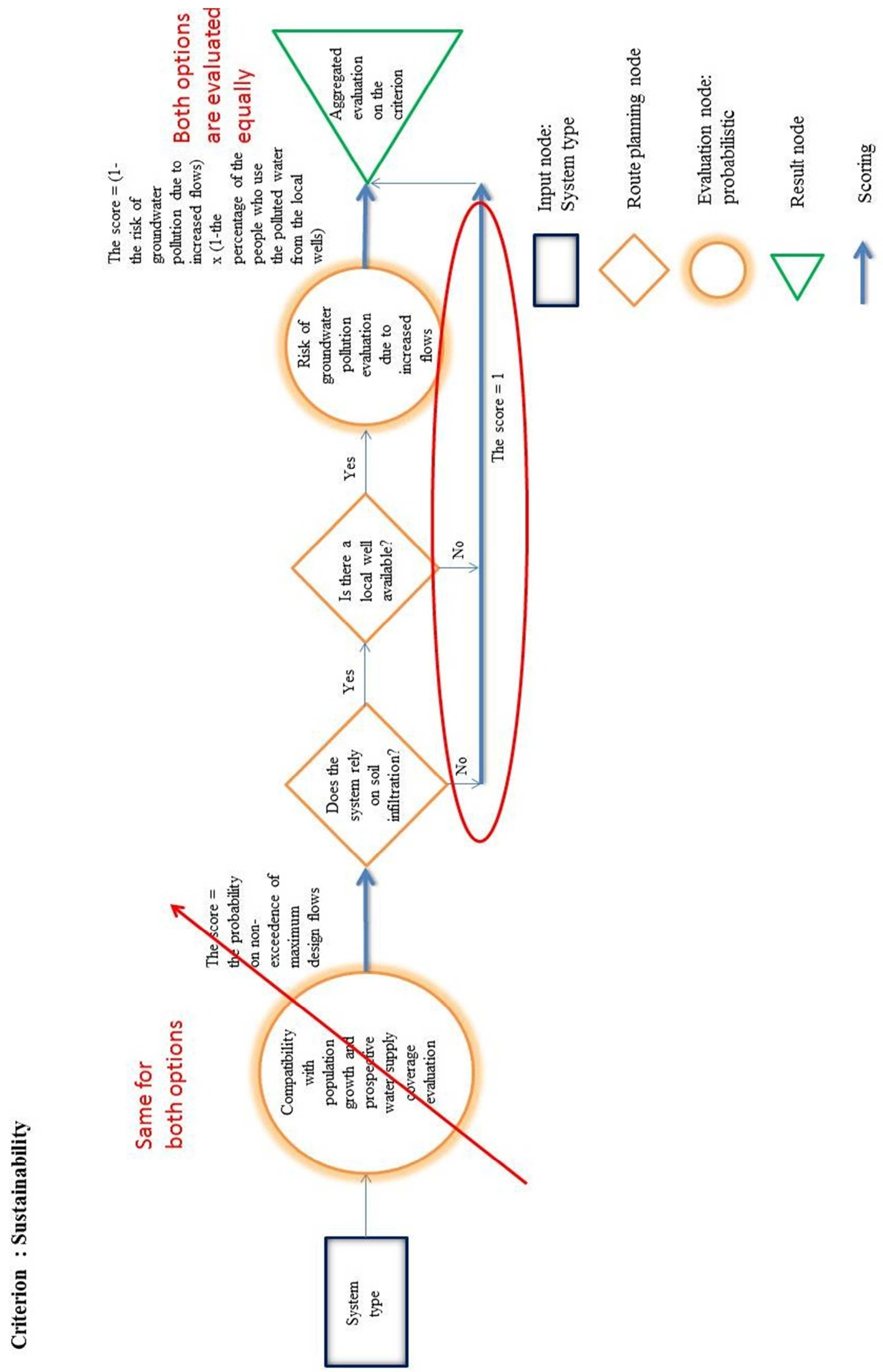


Figure 33: An example evaluation of pour-flush toilets with septic tanks and settled sewers versus eco-san facilities with respect to sustainability criterion, for an example area in Nyalenda settlement, Kisumu, Kenya

8.1.3. Final evaluation on the sanitation options for Nyalenda

With the assessments that were performed in section 8.1.2 with respect to different evaluation criteria (and summarized in Table 8), it can be concluded that based on the available information and the assumptions (which were made due to lack of data in this example), pour-flush toilets followed by septic tanks and settled sewers are evaluated to be the option that is more likely to indulge the objective of the system (compared to eco-san option). The biggest factor that contributes to this result is the missing link between the toilet products and reuse centres, if the eco-san facilities were going to be implemented. Without closing the nutrient cycle, which is one of main aims in selection of eco-san facilities among other sanitation options, the implementation of this option may not be justified. In addition to that, real practice data that indicate a large probability of incorrect usage of eco-san facilities by the users, in spite of training provisions in advance, add to the uncertainty in success of these facilities in fulfilling their objectives.

Table 8: Overview of the evaluation results for sanitation options for an example area in Nyalenda, Kisumu, Kenya

Evaluation Criterion	Pour-flush toilets + septic tanks + settled sewers	Eco-san facilities
Exposure to health hazards	reference	> reference
Accessibility	reference	0.1 * reference
Reliability	reference	0.6 * reference
Sustainability	reference	reference

Improvement measures that can deal with the shortcomings of eco-san facilities in this case are rather complicated as they are tangled with a network of social, political and economic factors with so many players involved.

Nevertheless, it should be taken into account that pour-flush options have their drawbacks as well, as revealed in the evaluations. Sludge removal from the septic tanks, even in case of using mechanical facilities is a high risk activity with respect to health concerns. However, the small number of people affected by this activity and the risk mitigation measures that could be easily practiced in this regard, may reduce the overall risks. On the other hand, availability of adequate water supply in the area and the existence of Nyalenda waste stabilization ponds that are currently under-utilized and can receive the flows from septic tanks, support the selection of this option.

The impact of the uncertainties in the evaluation scores can be assessed by using different score values (within the range that is likely to happen) and seeing the impact on the final assessment.

It should be mentioned that the costs of both options shall also be calculated separately and will indeed be a highly influential factor on the final decision to be made. Local policies and regulations are also another influential factor which shall be taken into consideration in decision-making.

9. Conclusions and Recommendations

The probabilistic evaluation framework, as suggested in this thesis, is an alternative approach in addressing the complicated selection process of sanitation options in low-income areas. While most decision-making frameworks developed so far are characterized by intuitive judgments through assuming the outcomes and conditions that most 'represent' a sanitation option- with little or no regard to the factors that limit the predictive accuracy- this approach tries to maintain an objective view on matters. It tries to refer to the real world examples where various sanitation options have been implemented and considering them, evaluates the options based on the probabilities that the expected outcomes occur in practice.

Although this impression may exist that quantification of probabilities in the assessment process is not possible, this work managed to suggest some methods to quantify the assessments by assigning some functions to the probabilities of occurrence for each indicator. These functions also overcome the inconsistency in the risk levels and the evaluation scores that are vaguely defined and shift from one value to another in some of the previous decision-making support tools for sanitation.

The case study on selecting sanitation options for the Nyalenda unplanned settlement area in Kisumu, Kenya, indicated that while a sanitation option (eco-san in this example) may be known for fulfilling a certain task by definition (recovering toilet products in this example), upon implementation of probabilistic evaluation it may turn out that the site conditions are not likely to allow for the expected outcomes to occur and therefore the option is of no priority in the decision-making. The case study also highlighted the vitality of having access to various information and data, in order to be able to implement the probabilistic evaluation in a justified manner. It was revealed that with probabilistic evaluation, decision-making will not be a desk-top study based on the definitions and characteristics of sanitation options as described in references. Rather, it requires site-specific data (technical, social and institutional) and a well-planned monitoring and evaluation program. Lack of these data add to the uncertainty of the evaluations as they would be based on some rough assumptions that may or may not be valid in reality.

The process of evaluation, apart from leading to a sanitation option which is more likely to fulfil the objectives of the system, uncovers the shortcoming that may exist in the options to be selected. To deal with them, risk mitigation or improvement measures that are presented in this thesis will channel the decisions in a way that the likelihood of success of the selected systems would increase.

In order to further test and develop the evaluation methods as presented in this thesis the following recommendations would be applicable:

1- Several assumed relations in this thesis (e.g. risk of microbial pollution of groundwater versus travel time) shall be further tested and validated.

2- A decision-making process shall entail the information and observations from real cases that are in operation. For this purpose, monitoring and evaluation programs shall be performed once the sanitation options become operational. The data from monitoring can then be used for improvement of the existing systems and also in decision-making for other similar projects.
3- Creation of a database within universities, research companies and governments that records the outcomes of sanitation projects under the local conditions, provides a great source of information to feed the decision-making process. Detailed record of local conditions (e.g. geohydrological conditions, social specifications) would facilitate sound assessments.
4- Although cost evaluation of sanitation options is excluded in this thesis, it needs to be addressed as an influential factor on the final decision to be made.

A list of the type of information that is required to perform the probabilistic evaluation as presented in this thesis is available in Appendix II of this report. However, this list may be further updated and refined based on new findings or new methods that would be suggested for quantification of probabilistic evaluations.

In the end, it may be worth reminding that the complete transition of the urban living into something that we today call sanitized, took several decades in the developed world; while the background for this change was already in place, stemming from the industrial revolution in those countries. Today, after a few centuries, implementation of new systems and renovation and modification of the existing systems is still an on-going process in those countries, meaning that decision-making for sanitation systems is also an evolving process. Therefore, expecting quick outcomes in the developing world, where the background for sanitary transitions is not yet well-established in many cases, may be far from reality and frustrating. Instead, the situation shall be looked upon as a dynamic process in which refining and evolution of the sanitary decisions need to be highlighted and worked out.

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Appendix I: Description of Sanitation Facilities

Dry toilets

Dry toilets consist of various toilet types including: traditional pit latrines (TP), ventilated improved pit latrine (VIP) and raised pit latrine (RP). In dry toilets, water is not used for the transport of excreta. A hole is dug under the squatting place to which excreta is directly dropped. Except for lined pit latrines, in which seepage of the leachate into the soil is prevented, in other dry toilets types the leachate seeps in to the soil, while the dry matter remains in the pit. The pit has to be emptied when full.

The sludge accumulation rate for dry latrines is at maximum between 60 to 90 litre per person per year depending on the anal cleaning material being degradable or non-degradable (Franceys et al., 1992).

The produced biogas in these latrines escapes into the atmosphere or is dispersed into the surrounding soil. The bad smell and the flies that are attracted to these latrines limit their indoor execution. They are mostly located out of the buildings in an open area.

Traditional pit latrine

Traditional pit latrines are the most basic type of dry toilets, consisting of a pit under the ground where the urine and faeces are dropped and a squatting plate as a user interface. In unlined pits, the leachate seeps into the soil while the dry matter remains in the pit and shall be emptied when piled up.

Ventilated improved pit latrines (VIP)

Ventilated improved pit latrines have been developed to deal with the problem is bad smell and flies in the traditional pit latrines. A vent pipe is extended from the pit to the top of the toilet superstructure, and is equipped with a fly screen. However, they are considerably more expensive than simple pits, since a ventilation pipe and full superstructure are required (Franceys et al., 1992).

VIP latrines can be made indoors, provided that the vent pipe is bigger (about 150 mm) compared to the VIP latrines which are made outdoors (Mara, 1996).

Raised pit latrines

Raised pit latrines are developed to deal with the problem of flooding in traditional pit latrines in areas that are prone to flooding. They are made at a higher level above the ground surface.

Urine diverting dry toilets (Eco-san toilets)

In eco-san toilets faeces are transferred to a lined chamber below the toilets where dehydration takes place. This leads to reduction in the volume of the faeces and their partial decomposition. Ashes, charcoal or other water-absorbing material will be added to facilitate dehydration and increase the pH so that reduction in pathogens, especially *E.coli* and *Ascaris* eggs is also achieved (Chaggu, 2004). The high carbon content of such material also ensures that a high C:N ratio is obtained, so that sufficient nitrogen is retained to make a good fertilizer of the faecal sludge. The duration of such primary treatment is usually in the order of a few months (Winblad and Simpson-Hébert, 2004).

Secondary treatment of faeces occurs on-site in rural areas (in the garden of the owners, where it can be stored for 1-2 years) or off-site where it is collected and handled by an organization. This step may include composting, extra storage, lime addition, etc. In areas where the temperature rises up to 35°C, total storage time (including primary treatment) of 1 year can lead to almost complete elimination of bacteria and substantial reduction of viruses and parasites (Winblad and Simpson-Hébert , 2004). Where there is concern about the persistence of intestinal worm eggs, carbonization or incineration as the secondary treatment will ensure a sterile product (Winblad and Simpson-Hébert , 2004).

Urine is collected separately from the faeces using a different hole (funnel) in the squat pan. The urine could be immediately used to fertilize the crop by the family as it poses little health risks (Winblad and Simpson-Hébert., 2004). It can also be stored so that it is collected afterwards to be used as liquid fertilizer. However, in some designs, it is also possible to collect urine and faeces together from one outlet but further separate them using the perforated floor which lets pass of the liquids (Winblad and Simpson-Hébert., 2004). But it should be considered that collection of faeces and urine together will result in contamination of the urine due to its contact with the faeces and therefore it shall be treated before being used as a fertilizer (Winblad and Simpson-Hébert, 2004).

In cultures where water is used for anal cleaning, the water can be collected separately from the faeces, through the use of another hole on the squat pan which shall be used when the user is going to clean him/herself. This water can be treated in an evapo-transpiration bed near the toilet for instance (Winblad and Simpson-Hébert, 2004).

Separation of urine and use of water-absorbing material are the distinctions between eco-san toilets and dry latrines, making the faecal sludge from eco-san easier to transport and reuse (because high amount of nutrients are retained).

Wet toilets

In wet toilets, water is used for flushing urine and faeces, utilizing a pipework. Some of the flush water remains in a U- trap which maintains a water seal that can prevent bad odour and flies from entering the toilet. Wet toilets consist of pour-flush and cistern-flush toilets.

The water consumption in pour-flush toilets is about 9 litres per person per day and in cistern-flush toilets about 40 litre per person per day (van Buuren, 2010).

Pour-flush toilets

Pour-flush toilets with direct soil infiltration use a pit for infiltration of the leachate and accumulation of faecal sludge. The pit works in the same way as in dry pit latrines with the difference that higher hydraulic loading rates are imposed to the soil due to use of water.

Pour-flush toilets without direct soil infiltration may be connected to septic tanks, where the human wastes will be directed using flush water. See the description of septic tanks in this regard.

Cistern-flush toilets

In cistern-flush toilets the excreta is flushed away from the toilet using a large amount of water (about 40 litre per person per day). It has a factory-made user interface and consists of a water tank that stores the flush water. The water is released by pushing a button or pulling a lever.

Bio-latrines

Bio-latrines are a type of pour-flush toilet made with the intention of recovering biogas from digestion of faecal matter. Black water is transferred via a small pipework to the bottom of a digester, which is a sealed tank where slow mixing of blackwater with the sludge occurs, using the small turbulence caused by the entering blackwater and by the produced biogas that flows upwards in the reactor. In an anaerobic biological treatment, the faeces are digested and a stabilized sludge is produced which can then be transferred to a slurry tank from where it could be carted away. The biogas could also be collected from the top of the digester and used for cooking or electricity production.

When utilizing the biogas is concerned, bio-latrines shall be implemented in communal toilets. Chaggu (2004) states that the gas produced is a bio-latrine used by 50 people is only sufficient to cook 3 meals for 5-6 persons.

The digested sludge can be reused as fertilizer, however, the pathogens are not completely removed in the digestion process. Depending on the reuse options, post treatment may be required. Sludge drying beds which utilize UV radiation for drying of the sludge and disinfection can be a good option in locations where long sunshine hours exist (as Chaggu (2004) recommends for Tanzania).

Septic tanks

Septic tanks are usually built under the ground and receive wastewater from the toilets and in some cases also the household wastewater. They work with flush toilets (and not the dry ones), however the water supply may be limited or intermittent (van Buuren, 2010). The hydraulic retention times are in the order of a few days (1-3 days as mentioned in Mara,1996). During this period the solids settle in the bottom of the tank where they are digested anaerobically. The tick scum layer formed on top of the septic tank helps to provide anaerobic conditions in the tank (Mara, 1996). They are commonly constructed with brickwork or block work and internally water-tightened with cement mortar.

The flow in the septic tanks is horizontal with the influent entering from one side and the effluent going out from the other end. The effluent from the septic tanks is the supernatant of the tank that is either soaked into the soil via the soakage pits or conveyed off-site via the settled sewers. Settled sewers are the conveyance method under the conditions that the soil infiltration cannot be applied.

High flows in to the septic tanks may cause suspension of the settled solids and increase the suspended solids amount in the effluent (Franceys et al., 1992). A solution to this is using double compartment tanks in which the suspended solids in the effluent from the first compartment can settle again in the second compartment (Mara, 1996).

The effluent from the septic tanks before infiltration into the soil can be treated in an up-flow filter with coarse aggregate medium. Mara (1996) states that in India, it has been observed that these filters are capable of reducing the BOD in the effluent up to 70%. COD removal efficiency in septic tanks is about 40% (van Buuren, 2010).

An alternative to soak-pits are drainage trenches which increase the infiltration area (so applicable to soil with low permeability) and can be built shallower than soak-pits and therefore increase the attenuation of pathogens in the subsurface before they reach the groundwater table (Howard et al., 2006). However, they require a larger area to construct and the costs will be increased.

The sludge accumulation rate in the septic tanks decreases with the number of the years. Mara (1996) mentions the value to be between 0.04 to 0.06 m^3 per person per year. The frequency of de-sludging is usually in the order of 1-5 years (Mara, 1996). During de-sludging, water content of the tank is also removed along with the sludge. The flow of the septage (mixture of sludge + water) is about 0.11 m^3 per person per year (van Buuren, 2010).

Settled sewers

Settled sewers, unlike conventional sewers, are not designed for self-cleansing velocities because a large part of the solids are already removed previously (in septic tanks). They can then be constructed with less gradient which means shallower excavation depths for these sewer types. The pipes also have smaller diameters. If pumps are used to convey the sewage, the pumps could be normal water pumps, unlike conventional sewers in which solid-handling pumps have to be used (Mara, 1996).

Simplified sewers (Condominial sewers)

The concept of simplified sewage was mainly developed in 1980s in Brazil, in which smaller pipe diameters and flatter gradients in shallower depths were used compared to conventional sewage systems. Also the piping is located under the housing blocks or in the pavements rather than in the middle of the roads (as in conventional sewers) resulting in smaller pipe lengths being used. The costs are therefore reduced by about 50% compared to conventional systems (Mara and Broome, 2008) due to smaller pipes, shorter pipes and less excavation resulting from flatter gradients. They are suitable for high-density low-income areas where there is no sufficient space for on-site sanitation for individual households.

Conventional sewer systems are designed based on the required self-cleaning velocity whereas simplified sewer systems are designed based on minimum shear stress required to keep the solids in suspension and avoid deposition in the pipelines. From this minimum value, the minimum gradient could be calculated and from that the diameter is calculated as well.

The concept of simplified sewers is being backed up by the arguments that claim conventional sewage systems are overdesigned and are based on conservative assumptions. Mara and Broome (2008) mention that in a survey in UK on 200 conventional sewer lengths, it had appeared that a higher proportion of the sewer lines which had the gradient in the recommended range had experienced blockage than the steeper or flatter ones. This means that in practice, no relation could be observed between the sewer blockage and the sewer gradient. In another example, Ackers et al. (cited in Mara and Broome, 2008) mention that with relying on a single value for self-cleaning velocity, the calculated diameters tend to be overdesigned. A report from Brasilia show that the number of obstructions per kilometre are the same between condominial sewer systems and conventional systems (Melo, 2005).

When the sewer lines are located under the housing blocks (in the users' yard for e.g.), although the pipe lengths are decreased (and so are the costs) but the disadvantage is that they are inaccessible to the utility companies and the maintenance responsibility is mainly put on the users (Melo, 2005). Removal of sewer blockage within the housing blocks is the responsibility of the users (Mara, 1996b).

Appendix II: List of Requirements for Probabilistic Evaluation of Sanitation Options Based on the Proposed Quantification Methods in this Thesis

To perform the probabilistic evaluation of sanitation options based on the quantification methods that are presented in thesis, the minimum required information are listed in this section.

Criterion: Exposure to health hazards

If water supply is from a local well without treatment:

- Soil properties (hydraulic conductivity, porosity)
- Thickness of the unsaturated zone
- Depth of the well screen
- Discharge rate and radius of the well
- Lateral distance between the well and the sanitation disposal location
- Hydraulic loading rate from the sanitation facilities
- In case of using WhAEM geohydrological model for capture zone estimation, binary base map of the underserved area
- Areal recharge rate

For all cases:

- Degree of microbial attenuation in faecal matter prior to exposure of waste workers (which is dependent on the storage time of faeces and the storage environment)

Criterion: Accessibility

If shared sanitation facilities are going be applied:

- Location of the toilet facilities
- Distance of the houses to the toilet facilities

If toilet products are going to be reused directly:

- Identification of reuse centres
- Percentage of the recovered products that is demanded in reuse centres
- Location of the reuse centres and their distance to the sanitation facilities
- Availability of logistics and transportation facilities for transferring the toilet products to reuse centres

Criterion: Reliability

- Routine hours of water supply (if there is a routine timing)
- Average rate of water supply failure (if there is no routine timing and water supply failure is a random event)
- List of possible incorrect uses of sanitation facilities by users

- Monitoring data on the number of incorrect uses of sanitation facilities that occur in the most available similar socio-cultural environment where the sanitation facilities were implemented previously
- List of the required O&M tasks for sanitation facilities and the required tools and equipment
- Repair time data for sanitation facilities based on local conditions (from which average repair time and the standard deviation would be derived)
- Annual O&M costs (based on local cost of tools and equipment, number of people for O&M activities, corrective and preventive maintenance time, mean time between failures, local labour-hour costs)
- Identification of financial resources for O&M activities, their contribution and their stability over a length of time
- Flood depth data over several years
- People's memory on flood depths if no recorded flood depth data is available
- Construction level of sanitation facilities on the ground

Criterion: Sustainability

- Population growth rate
- Prospective water supply coverage and flows (derived from the existing coverage trend for the location and water supply budget allocation for the considered location)
- Prospective wastewater flows resulted from population growth and/or water supply coverage

Delft University of Technology
Faculty of Civil Engineering and Geoscience
Department of Water Management
Section of Sanitary Engineering
Stevinweg 1
2628 CN Delft

www.sanitaryengineering.tudelft.nl