Getting a better grip on sanitation systems

Introducing a numerical model to identify, predict and mitigate hazardous events and measure the safety of on-site sanitation systems

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TU Delft

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by

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After graduating from high school at the age of eighteen, I volunteered in a small community in Nicaragua. During that time, I lived in the self-made house of my host family. It was during that period that I first encountered a pit latrine. As my project in Nicaragua lasted, I often wondered whether the pit would be hygienic and if it was not, whether my host family would know how to make it more hygienic. My admiration for my caring host family and their way of living has been the driving force behind this thesis.

From that moment on, sanitation has touched me close to my heart. Therefore, I feel very privileged to be able to contribute to the process leading to safe sanitation as part of my internship at the World Health Organization (WHO) and my final assignment within the track Water Management of the MSc. Civil Engineering at the Delft University of Technology. My research is executed in collaboration with the Joint Monitoring Programme for Supply, Sanitation and Hygiene (JMP) of the WHO and United Nations Children's Fund (UNICEF) in Geneva. Starting at the WHO HQ in Geneva during the Covid-19 outbreak has been an experience in itself. It was followed by the lock-down, which has been a learning process along the way. I find it incredible how much I have learned over the past seven months, and I would like to thank certain people for making this possible.

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Abbreviations

DSC Differential Scanning Calorimetry

GLUE Generalized Likelihood Uncertainty Estimation

JMP Joint Monitoring Programme for Supply, Sanitation and Hygiene

LLN Law of Large numbers

OAT One factor At a Time

OSS On-site sanitation

SDG Sustainable Development Goal

SSP Sanitation Safety Planning (SSP) manual for safe use and disposal of wastewater, greywater and excreta

UNICEF United Nations Children's Fund

VBA Virtual Basic for Applications

WHO World Health Organization

Summary

59% of the people in the world are not connected to a sewer system and use on-site sanitation (OSS) systems (UNICEF and WHO, 2019). The term "On-Site Sanitation" (OSS) is used to describe sanitation systems where the produced faecal matter is (partly) treated on the same location as where it is created. OSS is acknowledged as a sustainable solution to deal with faecal matter provided these systems are managed in a safe manner. Unsafely managed OSS systems are a threat for health and environment and thus an issue of serious concern. Because OSS systems are usually locally managed, limited information on the status of the OSS systems (including information on the safety thereof) is available on a larger scale. Therefore it is difficult to indicate how significant the problem of unsafely managed OSS systems is and where this problem is exactly located on the world's map. When there are data acquiring systems in place regarding, for example, the emptying frequency of OSS systems, the interpretation of these data does not always lead to an uncontested conclusion on whether an OSS system is safe or not.

In the literature on safe OSS systems, researchers measure and simulate multiple indicators that describe the behaviour of OSS systems. However, there is a lack of general understanding of how to apply these analyses for policymakers or regulators. The application of these analyses could: 1) be used as indicators to assess the safety of OSS tanks and contribute to the data collection of the status OSS of tanks; 2) help in formulating simple guidelines and recommendations on the emptying frequency; 3) help to improve the safety of OSS tanks.

The goal of this thesis is to assess if, and to what extent, scientific analyses on the behaviour of sludge in OSS systems can be applied to mitigate hazardous events.

The research question is as follow: *to what extent is it possible to develop easy and valuable guidelines on the safe emptying frequency of septic tanks from a numerical model that can mitigate hazardous events.*

Chapter 1 of this thesis will provide an introduction on the subject matter, whereas **Chapter 2** will highlight the theoretical background thereof.

To tackle the problem of unsafe OSS systems and to contribute to getting to safe OSS systems, it is essential to know what leads to unsafe OSS systems. **Chapter 3** translates established risk assessment into assessment for non-site specific situations. This will help in getting to a global overview of possible risks that contribute to unsafe OSS systems. With that as a starting point, a target could be created for global solutions to achieve safe systems. The methodology for this listing of hazardous events results from modules two and three of the *Sanitation Safety Planning manual for safe use and disposal of wastewater, greywater and excreta* (SSP) by Winkler et al. (2016). The risks assessment lists hazards, hazardous events and causes of hazardous events in a structured manner. Each cause of hazardous events has at least one or more mitigating measures.

Chapter 4 shows a prioritisation of the hazardous events which can be used as a starting point for researchers to allocate their research objectives on the unsafe aspects of OSS systems that pose the most substantial threat to the health of their users or exposure groups. Through a *structured* expert judgment, the risks of the seven most relevant hazardous events are estimated. The combination of expert judgments created a virtual expert that could estimate accurately and precise the risks of the hazardous events. This led to the identification of three high-risk hazardous events: groundwater pollution, local watercourse pollution and surface flooding. Providing a recommendation with a specific time after which an OSS system should be emptied and with the assumption that tank users would adopt these recommendations, could mitigate and impact the causes of all three high-risk hazardous events.

To propose the recommendation as mentioned above, **Chapter 5** offers a numerical model which can calculate the emptying frequency for different household sizes. The model simulates the fill rate in septic tanks. The sensitivity analysis shows that two characteristics (water content of settleable solids and the specific gravity of sludge) inside a septic tank serve as dynamical indicators of the fill rate and should require in-field measurements to obtain an accurate result from the model. The other eight identified characteristics can be approximated with a method called GLUE, that uses multiple Monte Carlo simulations. The numerical model simulates the performance of the septic tank with a correlation value of 0.98 and 0.9, compared with the values identified in the literature reviews. The calculated emptying frequency ranges between 1 and 20 years depending on the water content, the specific gravity of sludge, amount of users, and applied guidelines.

To make the results of the model accessible for tank users, tank managers or policymaker, a user tool was programmed in the Virtual Basic for Application (VBA) environment of Excel based on the results of the model. In this tool, users can receive a personal recommendation regarding their septic tank of interest in a simple manner depending on the size of the tank, the amount of user's, the water content of the settleable solids and the specific gravity of the settleable solids.

The research presented in this thesis opens a new door to dynamically measure the safety of OSS systems. The user tool allows for more personalised recommendations of the operational and maintenance requirements for users of OSS systems. The result may offer guidance to the users or managers of septic tanks for the required time to empty their septic tank. In additions, the tool could support policymakers to monitor and assess the safety of OSS systems, which will help to target intensive improvements and preventative/supportive solutions to regions or communities who will likely benefit most from them. Also, the user tool can help policymaker to generate profound guidelines toward septic tanks.

Contents

List of Figures

List of Tables

1

Introduction

"SDG 6.2: by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations" (General Assembly, 2015)

We are not there yet. In 2017, globally only four out of ten people used safely managed sanitation services. In Sub-Saharan Africa, this number was even lower at only two out of ten people. Even in Europe and North America, two out of ten people did not use safely managed sanitation systems (UNICEF and WHO, 2019).

Of the world's population, 59% of the people are not connected to a sewer system and use on-site sanitation (OSS) systems (UNICEF and WHO, 2019). The term "On-Site Sanitation" (OSS) is used to describe sanitation systems where the produced faecal matter is (partly) treated at the same location as where it is created, for example, a pit latrine or a septic tank. OSS systems have recently been acknowledged by the United States Environmental Protection Agency (USEPA) as a long-term sustainable solution to deal with faecal matter (USEPA, 2005), (Ward et al., 2019). However, the safety of users is often compromised. **Why and how to get there?**

The necessity of safe sanitation
Enhancing sanitation protects our environment and improves people's health, which converts into socio-economic development and the reduction of poverty (Nakagiri et al., 2016). Safe sanitation blocks diseases and promotes human dignity (World Health Organization, 2018). Sustainable Development Goal (SDG) 6 aims to "ensure availability and sustainable management of water and sanitation for all". In addition, SDG 6.2 aims "to achieve access to adequate and equitable sanitation and hygiene for all" (General Assembly, 2015).

Monitoring OSS systems: creates focus but currently not at full potential
Targeted solutions and incentives on the aspects and areas that are most relevant can help in fulfilling SDG 6. The monitoring of any progress, in, for example, the use of safe OSS systems, is an essential tool which creates clear focus points. Therefore, the WHO and UNICEF created the Joint Monitoring Programme for Supply, Sanitation and Hygiene (JMP). The JMP "produces internationally comparable estimates of national, regional and global progress on drinking water, sanitation and hygiene (WASH) and is responsible for global monitoring of the SDG targets related to WASH". However, currently, there is a large data gap for national and

global monitoring of these OSS systems (UNICEF and WHO, 2019). Governments, also in collaboration with the JMP, are attempting to set-up routine data collection programmes. However, it appears that it is unclear what aspects contribute most to safe OSS systems and what the main hazardous events are. Furthermore, when there are data collection systems in place, the interpretation of these data does not always lead to an uncontested conclusion on whether an OSS system is safe or not.

What is (un)safe sanitation?
The collection of data on the functioning of OSS tanks goes via census or household surveys (UNICEF and WHO, 2019). During these surveys, users often are requested to indicate the last time they emptied their tank. From the responses, it becomes apparent that the date at which the people emptied their OSS system for the last time, reaches far beyond the relevant design capacities of the OSS systems (Englund and Strande, 2019). How is this possible, and what does that mean? This is unclear. When acquiring data on desludging periods, the interpretation of these data is difficult since there are no generally accepted indicators or methods to determine after how much time a tank *should* be emptied (Appendix A.1).

These methods or indicators could, first of all, assess the functioning of OSS systems and determine whether a system is functioning safely or not. Secondly, the methods could help to collect information which could create a global overview of the status of OSS systems which will lead to a more targeted solution to help to achieve safe sanitation globally. Lastly, these methods could help policymakers to formulate recommendations and guidelines for safe operations and safe maintenance of OSS systems.

Keyterms and definitions in research goal and thesis outline

- **Easy to implement:** a solution that is feasible based on costs, ease of use, time/test and necessary technical expertise
- **Hazardous event:** an incident that leads or may lead to unsafe sanitation situations for OSS systems.
- **Numerical model:** a programme developed in Python which uses an equation for septic tanks of Al Momani (2015) to simulate the accumulation of sludge in septic tanks.
- **Recommended emptying frequency:** a specific time after which OSS systems should be emptied to avoid unsafe sanitation situations.
- **Safe sanitation:** a system that separates human excreta from human contact for all users, the local community, the wider community and sanitation workers.

Research goal and thesis outline
In the literature on safe OSS systems, researchers measure and simulate multiple indicators that describe the accumulation of sludge in OSS systems (Appendix A.1). These analyses have a positive influence on our knowledge about biophysical processes inside the system. However, there is a lack of general understanding of how to apply these analyses for policymakers or regulators. The application of these analyses could: 1) be used as indicators to assess the safety of OSS tanks and contribute to the data collection of the status OSS of tanks; 2) help in formulating simple guidelines and recommendations on the emptying frequency; 3) help to improve the safety of OSS tanks.

This research aims to assess if and to what extent the scientific analyses on the behaviour of OSS systems can be applied to mitigate hazardous events. To that end, this study will first identify the main hazardous events that determine the performance of safe OSS systems as well as the main operational and management measures to mitigate these events. Subsequently, the research will assess the ability to use scientific analysis to predict hazardous events and define operational and management measures which lead to recommendations to mitigate hazardous events.

With the following research question:

To what extent is it possible to develop easy and valuable guidelines on the safe emptying frequency of septic tanks from a numerical model that can mitigate hazardous events?

and the following sub-research questions:

- *What is the impact of a recommended emptying frequency on the hazardous events in respect of safe OSS tanks?* [1]
- *What is the recommended emptying frequency based on a numerical model?*
- *How can we test the status of an OSS tank based on the numerical model?*

This thesis consists of four core chapters (chapter 2-5) and a general discussion in chapter 6.

Chapter 2 provides a review of studies on the key elements of OSS systems and the accumulation of sludge. Also, it presents an overview of recent developments and novel opportunities to describe the behaviour of sludge in OSS systems, as well as it shows how this affects the policy guidelines regarding recommended emptying frequencies.

Chapter 3 presents a global overview of possible risks that contribute to unsafe sanitation which could lead to focused solutions to achieve a safe status of OSS systems. Four mitigating measures can help overcome these risks. One of these mitigating measures is a recommended emptying frequency.

Chapter 4 indicates the importance of a recommended emptying frequency by estimating the highest risks of OSS systems by a structured expert judgment. The relevance of a recommended emptying frequency is high when it can help mitigating high risks of OSS systems.

Chapter 5 shows that a developed numerical model can measure the fill-up rate of OSS systems by using a limited amount of in-field measurements. The model calculates recommended emptying frequencies which can mitigate risks introduced in chapter 3. In order to make the insights of the model usable for different kind of users, a simple tool is developed that provides personal recommendations regarding the emptying frequency of septic tanks.

These methods and findings will be critically discussed in **chapter 6**, containing a summary of the main findings and implications for future research.

[1] All of this, on the assumption that users of OSS systems would follow-up on the recommendations.

2

Theoretical background

This chapter describes the theoretical background of this thesis in the following paragraphs: (i) the essential concepts of OSS systems; (ii) the content entering OSS systems; (iii) descriptions of containment systems; and (iv) involves an explanation of sludge accumulation and the factors that influence that process. In addition to this chapter, Appendix A provides a summary of studies that assesses the sludge accumulation, the published guidelines regarding the emptying frequency and the differences in guidelines between various countries.

2.1. Key concepts of safe OSS systems

Tilley (2014) describes sanitation as a “multi-step process in which human excreta and wastewater are managed from the point of generation to the point of use or ultimate disposal”. The sanitation system is a “series of technologies and services for the management of these wastes (or resources)”(Tilley, 2014). Sanitation is split-up into two principal categories: off-site and on-site systems. An off-site sanitation system is a system which collects excreta and wastewater and subsequently conveys the wastewater and excreta away from the sanitation site to a facility which treats the sewage. The off-site sanitation systems rely on a sewer connection. An OSS system is a sanitation site which collects, stores and (partly) treat the excreta and the wastewater. This system does not involve a sewer system.

Safely managed sanitation implies secure management of excreta at each part of the sanitation service chain, including containment, emptying, conveyance, treatment and eventual disposal or re-use. This sanitation service chain is depicted in figure 2.1 (UNICEF and WHO, 2019).

Figure 2.1: Sanitation Service chain shows every step between faecal matter entering the sanitation chain to the end use (UNICEF and WHO, 2019)

2.2. Content entering OSS system

The content entering the OSS systems varies widely between and within countries, cultures and communities. These differences originate from users’ practices. For example, the type of anal cleansing material that is applied varies from water, toilet paper but also newspapers. Additionally, some communities utilise OSS systems for waste disposal; others use OSS systems strictly for faecal matter. In certain kinds of OSS systems, discrepancies arise from various groundwater levels. Other variations stem from fluctuating types and amounts of excreta and urine. These variations affect the biological and physical processes that occur (Mara, 1984).

Table 2.1: The study of Rose et al. (2015) compares the the wet and dry mass of faecal matter from low and high income populations. According to these results, the maximum and minimum weight of mass from high income countries is higher than that from low income countries

	Wet weight (g/person/d)		*Dry weight (g/person/d)*	
	Income = high	*Income = low*	*Income = high*	*Income = low*
Statistical values				
Median	126	250	28	38
Minimum	51	75	12	18
Maximum	796	520	81	62
Mean	149	243	30	39

The amount of excreta and urine generated daily varies significantly per individual depending on the consumption of water, the climate, the diet and the occupation (Franceys et al., 1992). Table 3.1 shows differences between the daily wet and dry-mass produced by humans from low and high-income populations (Rose et al., 2015). The table shows that the minimum mass of faecal matter can differ between high and low-income countries up to a factor of 2.

Faecal matter from a healthy person contains approximately 75% to 80% moisture. The organic materials in faeces include biodegradable (80%), readily biodegradable and slowly biodegradable materials (Butler and Payne, 1995). Generally, from the dry part of the faecal matter, 30% of the mass is active microorganisms. Also, a large part consists of intact cellular material. These materials come from active, dead or inactive microorganisms. (Buckley et al., 2008)

2.3. Descriptions of containments

A large part of the treatment of faecal matter takes place in the containment part of the OSS system. These containers are mostly located underground and are connected to the toilet. Throughout the world, people use a wide range of containment types. Below is a small description of the four different types of widely used containments.

Septic tank
A septic tank is a watertight chamber, typically made of concrete, fibreglass, PVC or plastic (Tilley, 2014). A septic tank system should have three components:

1. the septic tank. Within the septic tank, settling and anaerobic treatment occur. These processes reduce the solids and organic materials of the incoming sewage. Oil and grease (or scum) float to the top. The pathogen removal in a well functioning tank is only moderate. The outflow from the septic tank is known as septic tank effluent. Users need to take care of the periodical removal of the accumulated sludge and scum;

2. some form of drainage field (for example, absorption trenches comprised of pipes and gravel). Pipes transport the septic tank effluent to the drainage field; and

3. the subsurface or soil. The liquid from the drainage field (known as leachate) drains into the subsurface or soil below the drainage field. Within the subsurface, the leachate undergoes further in-situ treatment as part of its ultimate release to the environment or groundwater.

Fully lined storage tank
A fully lined tank is a watertight chamber without an effluent line. Within the tank, settling and anaerobic treatment occur. The pathogen removal in a well-functioning tank is only moderate. Users need to empty or exchange their fully lined storage tank frequently since there is no effluent line (World Health Organization, 2018)) (Tilley, 2014).

Partially lined pit latrines
This system collects and stores excreta and can be used with or without flush-water, depending on the toilet. Timber, bricks, concrete, stones or other materials plastered over the soil provides the partial lining. Stable soil is essential, which means that there are no sand or gravel sediments or free organic materials. The level of the pit is more than 2 m above the groundwater level, which prevents contamination of groundwater. The pit collects excreta and anal cleaning materials. The main processes inside the pit are leaching and microbiological degradation. When the pit is full, users might backfill it with soil and plant trees on top of it (World Health Organization, 2018)).

Cess pit/leach pit/leaking septic tank
This pit/tank consists of a covered, porous-walled chamber. Rock and gravel give the chamber stability and prevent the chamber from collapsing. The bottom of the tank contains sand and fine gravel and is more than 2 meters above the groundwater table, which prevents groundwater contamination. Water can slowly soak into the ground. The underground chamber accumulates settled effluent, after which it infiltrates into the neighbouring soil. The main processes inside the chamber are filtration by the matrix of the soil and digestion of organics through microorganisms.

2.4. Accumulation rate of sludge

Sludge accumulation is a very critical part of the operating of an OSS system (Al Momani, 2015), (Nnaji and Agunwamba, 2012). The sludge accumulation determines the performance of a system such as the quality of the effluent but also the necessary time between desludging (or emptying frequency). The accumulation of sludge depends upon internal and external factors. An example of an internal factor is the growth of biomass in the sludge, which changes over time and has an impact on the decomposition of microorganisms (Abusam and Keesman, 2009). Also, sludge is very consolidating and compressing, which will decrease the accumulation rate over time. The next section describes the main external factors that affect the sludge accumulation and thus the emptying frequency (Abusam and Keesman, 2009). Appendix A provides an overview of the studies that assess the sludge accumulation and show the discrepancy between different authorities regarding the recommendations of emptying frequencies.

Main external factors affecting the sludge accumulation
The main external factors that affect the sludge accumulation are the method of anal cleansing, the connection of black or greywater, the evaporation, precipitation and temperature, the nature of the diet, the soil conditions and the retention time. The underneath section presents further descriptions of these factors.

- **Type of anal cleaning** Some countries prefer anal cleaning with water, other with (news)papers or other materials such as plastic bags. These materials consist of a different volume and biodegradability (Franceys et al., 1992).
- **Use of blackwater or greywater** Blackwater contains everything that enters a toilet (e.g. faeces, urine, toilet paper). Greywater includes all wastewater in households or offices without the content that enters a toilet (e.g. showers, washing machines, sinks). The adding of greywater can result in a difference in the rate of sludge accumulation. The adding of greywater can increase the water content in the tank. Also, chemicals that are present in the effluent kitchen or bathroom water can hinder the activity of bacteria in the tank and subsequently, increase the accumulation rate of the sludge.
- **Evaporation, precipitation and temperature** Evaporation will release moisture from pits. The rate of evaporation depends amongst others on the temperature and humidity. Heavy precipitation can fill a pit quickly. Also, the temperature in the OSS system affects the rate of sludge accumulation. A report addressed to Water Resource Commission, stated that a 10 °C rise in temperature would increase the metabolism rate by a factor of 1.8 (Norris, 2000), (Franceys et al., 1992). This will decrease the accumulation rate significantly.
- **Dietary** The diet of users affects the concentrations of BOD and COD in the OSS system. Also, the amount of carbon, nitrogen and phosphorous will affect the biological processes. These depend on the protein and carbohydrate intake of the individual (Franceys et al., 1992).
- **Soil conditions** The amount of water that flows out of a pit latrine depends on the permeability of the soil. For septic tanks, the permeability of the leach field will affect the amount and quality of the water that infiltrates.

3

Identification of hazardous events

Abstract

Background
Safe sanitation separates human excreta from human contact in every step of the sanitation chain. In order to achieve safe sanitation, it is essential to know what contributes to unsafe sanitation. There are well-established methods to assess the risks of a particular OSS system at a specific location. Because of that, the solutions become specific for that particular location which makes it difficult to apply the solution to other locations. Translating the established risk assessments into assessments for non-site specific situations, we hypothesised that this would help in generating a global overview of the main risks that contribute to unsafe sanitation. On the basis hereof targets can be set for global solutions to help to achieve a safe status of OSS systems.

Method
The methodology for this listing of hazardous events results from modules two and three of the *Sanitation Safety Planning manual for safe use and disposal of wastewater, greywater and excreta* (SSP) by Winkler et al. (2016). The risk assessment lists hazards, hazardous events and causes of hazardous events in a structured manner. The assessment starts with the agent that has the potential to cause harm; the agent is a hazard (e.g. pathogens released to a river). A hazardous event is a situation that can lead to the presence of the hazard (e.g. solids discharged from the tank). The hazardous events can occur as a consequence of several causes (e.g. the tank was full of sludge). Finally, these components are brought together in an overview, which can be used by policymakers or tank users.

Results
Currently, five potential hazards have been identified which can impact the health of four exposure groups. Eight hazardous events can lead to the occurrence of each hazard. Whereas each hazardous events has up to twelve causes. There are five categories identified to mitigate these causes.

Conclusion
Non-site specific risk assessment leads to a global overview of the main risks that contribute to unsafe sanitation. The overview lists the possible hazards, hazardous events and its causes. The overview also shows measures to mitigate these causes. A non-site specific risk assessment can not grasp all risks in its entirety in one assessment since sanitation risks are, in its essence, always related to a particular site or location. Researchers could create limited scenarios which include the most crucial site-specific characteristics. Applying the same risk assessment to these scenarios could create a more comprehensive overview of the risks that contribute to unsafe sanitation.

3.1. Introduction

Researchers and policymakers have not yet found a simple and straightforward method to establish safe operation and maintenance requirements for OSS systems (Appendix A). In order to achieve safe OSS, it is essential to know what risks contribute to unsafe OSS (Winkler et al., 2016). There are well-established methods to assess sanitation systems on particular locations (Stenström et al., 2011), (Winkler et al., 2016). However, these risk assessments generally lead to an overview of the main problems in a particular location, which leads to site-specific solutions. Due to that, it makes it difficult to use the solutions or implication from one location and implement it at another location, which seems inefficient. Translating the site-particular assessments into assessment for non-site specific situations leads to a global overview of the main risks that contribute to unsafe sanitation, which can ensure that global measures control the most significant health risks.

The analysis aims to have a clear overview of the principal risks of OSS tanks and the primary operational and management practices to mitigate these events. Identifying the factors in the containment processes that most affect sanitation hazards can lead to an appropriate target for risk management strategies and research directions. The resulting overview can be used as a starting point for the creation of these operational and maintenance requirements.

The global risk assessment, created according to the method described by Winkler et al. (2016), will create an overview of the primary health hazards, hazardous events, the causes of hazardous events and determines possible measures to control these causes. According to the applied method, the hazardous events have a risk descriptor, which shows whether the events have a high, medium or low risk. Chapter 4 explains the prioritisation of hazardous events based on structured expert judgements.

The focus of this assessment is on the containment part. Even though, the diagram of *Guidelines on Sanitation and Health*, (World Health Organization, 2018) in figure 3.1 shows that safely managed sanitation implies safe management of excreta in every step of the sanitation chain, which includes containment, emptying, conveyance, treatment and eventual disposal or re-use (UNICEF and WHO, 2019). The analysis assesses four types of containments: a septic tank, a fully lined storage tank, a partially lined pit latrine and a cesspit/leach pit/leaking septic tank. Chapter 2 gives more information about these systems.

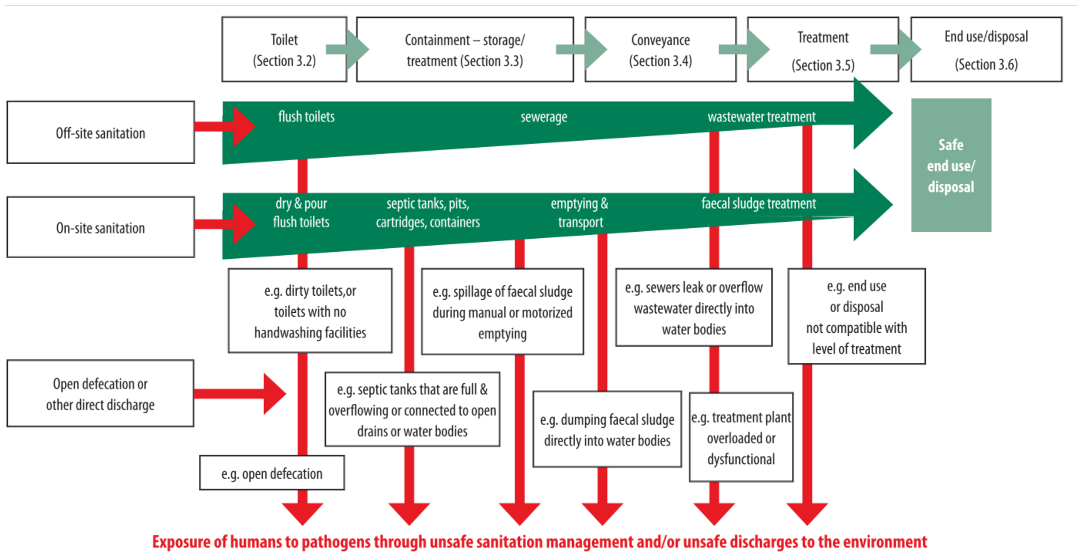

Figure 3.1: Excreta flow diagram showing examples of hazardous events at each step of the sanitation service chain (adapted from Peal et al. (2014)), reprinted from World Health Organization (2018)

3.2. Method: risk assessment

The methodology developed for this risk assessment results from modules two and three of *the Sanitation Safety Planning (SSP) manual for safe use and disposal of wastewater, greywater and excreta* by Winkler et al. (2016) and from *Guidelines on Sanitation and Health* by World Health Organization (2018).

Module 2 of the SSP manual, suggests a detailed description of the system with the characterisation and path of waste fraction from the point of generation or upstream boundary, to its use or disposal at a downstream limit. The guidance note 2.4 of the manual proposes an identification of the different waste fractions and associated potential health hazards. Since each hazardous event has various causes, each hazardous events also has different mitigating approaches. Therefore, according to Module 3 of the SSP manual, hazardous events and related exposure groups are also identified with its specific approach to mitigate the risk.

This assessment ultimately leads to an overview in a spreadsheet format that can be used by sanitation users or policymakers. The analysis assesses four types of containments: a septic tank, a fully lined storage tank, a partially lined pit latrine and a cesspit/leach pit/leaking septic tank. Chapter 2 explains more about these containment systems.

System boundaries, waste fractions and exposure groups
The system boundaries are the area delimited by the in and, if present, the outlet of the tank. The identified waste fractions of the tanks are blackwater such as urine, faeces, flush water, dry-anal cleansing material, anal cleansing water and greywater. Greywater denotes wastewater without faecal contamination, i.e. sinks, showers, baths, washing machines or dishwashers. The definition of the identified exposure groups is according to *Guidelines on Sanitation and Health* (World Health Organization, 2018):

- **sanitation system users**: all people who use the storage tank;
- **local community**: anyone who is living near to, or downstream from, the sanitation;
- **wider community**: the wider population (e.g. farmers, lower-lying communities) who are exposed to (e.g. through recreation or flooding) or use sanitation end-use products (e.g. compost, faecal sludge, wastewater) or consume products (e.g. fish, crops) produced using sanitation end-use products intentionally or unintentionally, and may be exposed; and
- **sanitation workers**: all people responsible for maintaining, cleaning or operating (e.g. emptying) the storage tank or equipment.

Microbiological, physical and chemical waste fractions
Hazards of health connected with the sanitation chain may be micro, chemical or physical. Both the liquid and solids waste fractions were assessed separately but the fractions show similar results.

The liquid waste fractions in the systems are diluted excreta and urine. These both can consist of the biological hazards of viruses, bacteria, protozoa or helminths. The waste fractions do not consist of any potential chemical hazards. Malodours are possible physical hazards for both of the waste fractions.

The solid waste fractions include faecal sludge. The potential biological hazards are viruses, bacteria, protozoa, helminths and vector-related diseases. Winkler et al. (2016) describe vector-related diseases as: "diseases (e.g. malaria, leishmaniasis) that can be transmitted from human to human via insect vectors (e.g. mosquitos, flies)". No potential chemical hazards are arising from faecal sludge. The likely physical hazards of faecal sludge are sharp objects, inorganic materials and malodours.

3.3. Results and discussion

The risk assessment aimed to list hazards, hazardous events, causes of hazardous events and mitigating measures for four OSS tanks: a septic tank, fully lined storage tank, cesspit and pit latrine. The results indicate five potential hazards, eight hazardous events, twelve causes of hazardous events and five measures for each of the four OSS tanks.

3.3.1. Hazards

This study considers the hazards unrelated to site-specific conditions. The results of the hazards, presented in table 3.1, show that there are four main hazards for OSS systems. The hazards were derived from the liquid and solids waste fraction shown in the previous section.
There is no specification about different types of bacteria, viruses, protozoa or helminths. All pathogens that are present in excreta can pose a health risk. Stormwater, river water and industrial wastewater are excluded from this risk assessment since these fractions are outside the system boundaries. However, these could also pose potential chemical hazards when toxic chemicals or heavy metals are released to the environment.

Table 3.1: Four potential health hazards are listed based on the liquid and solid waste fractions

	Hazards
1	Bacteria, parasitic protozoa, viruses, helminths and vector related diseases released to the environment
2	Inorganic material released to the environment
3	Malodours
4	Sharp objects released to the environment

3.3.2. Hazardous events

Each hazard can be caused by different hazardous events. Table 3.2 lists the main hazardous events. Appendix C presents the linkage between hazards and hazardous events. The hazardous events can occur during regular functioning of the system, a sudden failure or accident, and/or during a seasonal or climate-related event. The next section presents a detailed description of the causes of hazardous events.

Backing up of sewage and surface flooding can seem ambiguous since sewage in both cases is entering the surface. The differences between the two is that surface flooding is interpreted as wastewater flowing to the surface. Whereas backing up of sewage means that the sewage

3.3.3. Causes of hazardous events

There are 12 causes of hazardous events listed in table 3.3. One or more causes can lead to hazardous events, which lead to hazards (table 3.1). Appendix C presents the linkage between the hazards, the hazardous events and causes of hazardous events. This list could be extended by doing field research and asking users of OSS systems about the main problems they encounter. One of the main sources of this listing is Butler and Payne (1995) and Stenström et al. (2011). The underneath description presents an elaboration and discussion on the hazardous events. The causes indicated in table 3.3 are divided into unsuitable design, inappropriate location and inadequate maintenance and usage

Table 3.2: Seven potential hazardous events

	Hazardous events
1	Settled solids discharged from tank
2	Surface flooding
3	Backing up of sewage
4	Groundwater pollution
5	Local water course pollution
6	Odour
7	Tank full/tank lifts

Table 3.3: Twelve causes of the hazardous events

	Causes of hazardous events		
1	Tank full of sludge	7	Proliferation of tanks in sensitivite area
2	Inefficient or undersized tank	8	Inadequate ventilation of drains
3	Leaking tank	9	Drainage field operating properly but system in unsuitable location
4	Pit collapse	10	Inadequate drainage field
5	Deliberate overflow connection made	11	Deliberate overflow connection made
6	Blocked drainage field	12	Sagging or blocked inlet

Unsuitable design
Many causes could attribute to the lack of design of an OSS system: for example, an inadequate drainage field, insufficient ventilation of drains, inefficient or undersized tanks or deliberately made overflow connections. In some old installations, there is not a drainage field installed at all. In other situations, percolation tests were never done or done insufficiently. Eventually, the drainage field could be too small to dispose of the effluent of the tank. When tanks are functioning inefficient, the design of the systems might be old, or the tank is undersized. This last part can also be because the number of users increased over the years, which leads to overloading. Deliberate overflow connections to watercourses are problems occasionally seen at old tanks, where the old tanks did not have a drainage field. Chambers that are not water-tight or build with insufficient quality of concrete or plastic can cause leakage because of cracks.

Inappropiate location
The use of inappropriate locations for OSS systems can cause pollution of waterways or groundwater. An inappropriate location means a site where the environmental conditions are not suitable for an OSS system. When there is a proliferation of tanks in a sensitive area, the effluent does not reach the water table but quickly drains to a watercourse, which causes pollution to the waterway. Groundwater pollution can also be problematic, mainly when the tanks are situated close to a borehole. Unsuited ground conditions can cause blocked drainage fields. Primarily during the rain season, this problem arises because the groundwater is saturated and the effluent will not drain away fast enough.

Inadequate maintenance or usage
Full tanks are associated with user failures. Tanks become full when owners do not empty them in time. Reasons for not emptying are that owners are ignorant or negligent of their responsibility. Sometimes owners are not aware that their sanitation facilities are connected to OSS systems. Other owners are reserved to empty their tank due to the desludging expenses. These owners rather wait until the noticeable problems develop. Also, tanks that are owned by multiple households have issues due to late desludging, because of the unclear responsibilities. Other user problems (mostly with old tanks) are deliberate overflow connections. The installation of these tanks was often without a drainage field. Other causes are sagging, or blocked inlet drains because of improper use (e.g. users that throw waste in the OSS system) or poor detailing of the construction.

3.3.4. Approaches to control the causes

There are five categories to control the causes of hazardous events. The categories are shown in table 3.4. Appendix C presents the linkage between the hazards, the hazardous events, their causes and the approaches to control the causes. The underneath description elaborates and discusses each of the five categories.

Emptying frequency
As explained in the previous section, users of OSS systems can be ignorant or negligent of their responsibility to empty their OSS systems. Users wait until noticeable problems develop, instead of focusing actively to be ahead of the issues that might arise. The location of the OSS system is sometimes hard to get to, which makes it difficult for users to assess the filling of the system. The nature of the systems, the processes of faecal matter, also causes negligent behaviour. A recommended emptying frequency for a specific household can lead

Table 3.4: Five approaches to control the causes of hazardous events.

	Approaches
1	Periodically emptying
2	Planned performance monitoring and asset maintenance
3	Design standards
4	Standard use procedures
5	Regulations

to more clarity for the users so that a desludging practiser can be approached in time to empty their system.

Planned performance Monitoring and Asset maintenance
A septic tank needs to be checked whether the system is still operating as required and designed. Monitoring and maintenance checks can include (EPA of Ireland, 2018):

- leakage at manholes and pipes;
- type of water entering the system as designed for;
- ponding at percolation area;
- pollution at drains or ditches; and
- odour nuisance.

Design standards
The usage of the system has to match the type and dimensions of the system. Design standards focus on the predicted hydraulic loading of the system. In section 2.2, an overview is given of the difference in the mass of excreta that enters the tank. In a study of Rose et al. (2015), the mass per person with low income was 50% higher than the mass of high-income people. Type and amount of water connected to the systems determine the tank dimensions. Design standards could create consistency and suitable systems that are appropriate for the usage of the system.

Standard use procedure
There is a substantial difference in the usage of OSS systems. Often, in low-income countries, the OSS system is also a place for waste. This impacts the filling rate of the tank significantly. Also, the amount of chemical that enters the tank can affect the biodegradability of the tank and thus, the sludge accumulation rate. Standard use procedures could encourage equal practices so that OSS systems operate more consistently.

Regulations
Not all OSS systems are suitable for every location. Regulation can encourage people to build their tanks at appropriate areas which meet the health and environmental requirements. Furthermore, inspections initiated by the regulator can lead to a stronger feeling of responsibility for the users and also give a more substantial overview of the status of OSS systems in a region or country. An example of regulations is that users need a permit before they can install an OSS system.

3.4. Conclusion

Non-site specific risk assessment can give a global overview of the main risks that contribute to unsafe sanitation. Based on the risk assessment, it shows that there are four main hazards, seven hazardous events, where each hazardous events is a consequence of one or multiple causes. In total there are five main categories of approaches that could mitigate these causes.

A non-site specific risk assessment can not grasp all risks in its entirety in one assessment since a number of sanitation risks are, in its essence, always related to a specific site or location. Researchers need to work on creating limited scenarios which include the most crucial site-specific characteristics. Subsequently, a similar risk assessment could be applied to the different scenarios, which can create an overview of the risks of specific hazardous events for these scenarios. This assessment could create a more comprehensive overview of the risks that contribute to unsafe sanitation, which can help in ensuring that global measures control these significant health risks.

The listing in this assessment shows the problems in OSS systems that could lead to health risks. Complementing the listed mitigating measures with practical approaches could help to improve the safety of users of OSS systems, which can contribute to a more wisely and more efficient distribution of scarce and costly solutions, targeting them to areas and populations who will most likely benefit from

4

Prioritisation of hazardous events and the relevance of a recommended emptying frequency

Abstract

Background
Prioritising hazardous event for OSS can be a starting point for researchers to allocate their research objectives on the unsafe aspects of OSS systems that pose the most substantial threat to the health of their users or exposure groups. One of the unsafe aspects of an OSS system is a system that has not been emptied for a (too) long time. Users of OSS systems are often not aware of the amount of time that *should* be between two emptying events. Translating the unclear time needed for an OSS system into a practical recommended emptying frequency may impact the risks posed to OSS systems.

Method
This study investigates the risks of seven hazardous events through structured expert judgments. Contrary to regular expert assessment, a *structured* expert judgment refers to an attempt to quantify the (un)certainty of experts judgments by means of seed questions (questions we know the answers of). The performance of each expert leads to a performance-based average weighting. The experts are required to make risk-estimations of the hazardous events. The experts that know most about this topic, and thus have a high performance on the seed questions, influence more the outcome than experts that know little or less about this topic. Different aggregation methods are compared, such as an equal weighting method or an optimized weighting system. Ultimately, this leads to a quantification of the risks of hazardous events. In the previous chapter, the causes and mitigating measures for different hazardous events are listed. One of the mitigating measures is a recommended emptying frequency. This study analyses whether recommended emptying frequencies impact high-priority risks.

Results
Thirteen experts completed the survey. The aggregated expert judgments give accurate and precise results. All weighting systems led to the same risk estimates for the hazardous events. Groundwater pollution, local watercourse pollution and surface flooding exhibited significantly higher risks compared to backing up of sewage, settled solids discharged from tanks, odours or a tank that lifts. All of the high-risk hazardous events could be mitigated with a recommended emptying frequency.

Conclusion
The aggregation of expert's judgments created a decision-maker or virtual expert that could create accurate and precise results. The virtual expert can prioritise the events. This leads to the identification of three high-risk hazardous events. Periodically emptying can mitigate and impact all these three high-risk hazardous events.

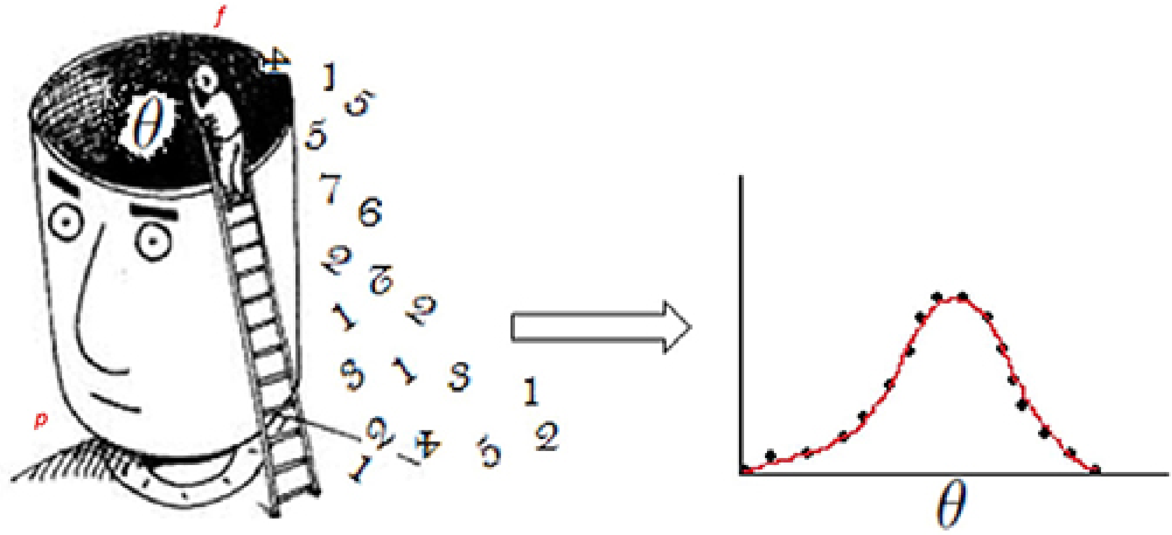

Figure 4.1: Illustration of the elicitation of priors. In the left image, a person's experiences influence his or her beliefs about the issue of interest (θ) where the person who elicits the information about θ want to capture the person's beliefs. The person who elicits the information need to quantify the knowledge of θ of the person and render it in a probability distribution.

4.1. Introduction

This analysis aims to prioritise the hazardous events, identified in the risk assessment, with structured expert judgement. From this prioritisation, the impact of a required emptying frequency, one of the mitigating measures of the risk assessment, is assessed. Structured elicitation is a method to increase objectivity in expert judgements. The elicitation is executed with an elicitation protocol, shown in appendix B, which also consists of the questionnaire. This elicitation uses the "Classical Model", which utilises performance-based average weighting for experts through calibration questions.

Structured expert elicitation increases the objectivity of expert judgements and scrutinises expert uncertainty. The use of expert advice is not a new process (Camerer and Johnson, 1997). However, unfortunately, experts always come with a significant degree of subjectivity (Kynn, 2008). The use of *structured* expert judgment refers to an "attempt to subject this process to transparent methodological rules, with the goal of treating expert judgment as scientific data in a formal decision process" (Cooke and Goossens, 2008). The purpose of the structured expert judgment is to simulate the knowledge of experts by capturing their uncertainty quantities in a probabilistic form. These probabilities reflect the degree of (un)certainty. Figure 4.1 illustrates the process of expert elicitation. The person on the ladder represents the researcher who wants to capture the expert's knowledge and beliefs through a probability distribution (O'Hagan et al., 2006).

4.2. Method: structured expert judgment with the Classical Model

Multiple scientists described steps to approach or protocols to execute structured expert elicitation. However, Jenni and van Luik (2010) reviewed multiple documents such as *Experts in uncertainty: Opinion and subjective probability in science* from Cooke et al. (1991), *Procedures guide for structural expert judgement in accident consequence modelling* from Cooke and Goossens (2000) and *Branch technical position on the use of expert elicitation in the high-level radioactive waste program* from Kotra et al. (1996). In this document the authors describe and recommend the steps for a expert elicitation with multiple experts. Jenni and van Luik (2010) summarise and conclude on approaches the authors have in common. These approaches are summarised and listed in table 4.1. The following section describe the execution of the steps.

4.2.1. Preparing the expert elicitation

This section explains the elaboration of each of the described steps of table 4.1.

Objective of the study, necessity and appropriateness of expert elicitation and elicitation method

Table 4.1: Seven steps for conducting an expert elicitation study reprinted from Jenni and van Luik (2010)

7 steps for the elicitation of an expert judgement	
1.	Define the objective of the study and determine whether expert elicitation is necessary and appropriate for meeting the study needs. Determine how the elicitation is to be carried out
2.	Select the experts
3.	Structure the assessment: identify and clarify the assessment issues, develop necessary assessment protocol
4.	Develop and provide the expert with background and training about assessment tasks, cognitive biases, and probability encoding concepts
5.	Conduct the elicitation itself and provide feedback about their elicitation results and their implications. In some approaches, this includes the opportunity for the experts to revise or update their assessment
6.	Use the individual expert's input to create an aggregate assessment of the quantities of interest, if desired. The results of the aggregation can be included in further feedback to the experts
7.	Document the assessment and results

The purpose of this study is to improve our understanding of the priority of hazardous events on the containment part of sanitation systems. There are seven main hazardous events as part of a more extensive comprehension of the leading risks for OSS systems. The non-site specific risk assessment of the previous section generated these seven hazardous events. Winkler et al. (2016) proposes that any semi-quantitative risk assessment should be taken into consideration by several individuals to increase the objectivity of the risk assessment. Because every expert has its own experiences with sanitation problems and risks, expert elicitation is appropriate. The elicitation takes place via an online tool called Survey Monkey, where the expert will give a risk estimate for each hazardous event in a probabilistic manner.

Expert selection
The project focuses on the risks of sanitation systems. Therefore, a global community of sanitation experts called the Sustainable Sanitation Alliance is approached. The network has around 12,500 individual members and 360 partner organisations with the goal to contribute to achieving the SDGs that promote sustainable sanitation. Also, sanitation experts from the Bill & Melinda Gates Foundation have been contacted. Both of these experts have longtime experience with OSS systems in different countries and settings. As part of their questionnaire, the experts also had the option to indicate their experience with sanitation. In the case, that experience in a different field is indicated or experience with only high-income countries, the expert is excluded from the questionnaire.

Structure of the assessment
For each hazardous event, the experts needed to indicate the risk level of a hazardous event, indicated in table 4.2 in a probabilistic range, which means that each expert gives its best (median), minimum and maximum risks score. The best estimate is presumed to be the 50-percentile. The minimum and maximum values are adjusted to a more conservative and hence wider interval according to the triangular distribution theory (Benini, 2017), (Greenberg, 2013), (O'Hagan and Oakley, 2004). According to this theory, the verbalised minimum for most experts is not their absolute minimum, but rather a value close to their 5-percentile. This theory also applies for the maximum and the respective 95-percentile.

Background information about assessment, biases and probability encoding concepts for the experts
Experts received the following background materials: a summary of the goals of the project and the elicita-

Table 4.2: Semi-quantitative risk assessment indicates the possible likelihood and severity for each identified hazardous event

		Severity				
		Insigificant *1*	*Minor* *2*	*Moderate* *4*	*Major* *8*	*Catastrophic* *16*
Likelihood						
Very likely	*1*	1	2	4	8	16
Unlikely	*2*	2	4	8	16	32
Possible	*3*	3	6	12	24	48
Likely	*4*	4	8	16	32	64
Almost certain	*5*	5	10	20	40	80
Risk score R = (L) x (S)		< 6	6-12		12-32	32 <
Risk level		Low risk	Medium risk		High risks	Very high risks

tion and a description of septic tanks (Appendix B). Psychology research has shown that experts are often subject to overconfidence biases (O'hagan, 2019). Jenni and van Luik (2010) suggest to include descriptions of the overconfidence bias to encourage expert to make their judgment accurately. Therefore, this is also included in the background materials. The experts could always return to the background materials. Before each question regarding hazardous events, a detailed description of the specific hazardous events was given. This protocol is shown in Appendix B.

Conduction of the survey

A questionnaire via an online programme *Survey Monkey* collected the expert's assessments, which is a good way for this time-limited research due to the administrative benefits. In that manner, every expert receives the same amount of information and answers the same questions. The built-up of the questionnaire is so that all experts will clearly understand all questions and tasks (O'hagan, 2019). All approached experts were educated or have experience with OSS systems. As explained in the previous section, to create clearness about definitions and wording, a so-called "elicitation protocol" was created. The elicitation protocol is a package of information which every expert needed to read. The package contains information about overconfidence biases, the elicitation format, calibration questions and elicitation questions. This protocol is shown in Appendix B.

The calibration questions test the knowledge of the experts. Experts with low calibrations scores will have a little (or a zero) weight for the final judgment. Section 4.2.2 elaborates further on the calculations of different expert weights.

The aggregate assessment of risk scores

A large group of experts is required to capture a wide range of opinions on the topic. Two distinct methods can obtain the probability distribution of a group of experts: single and behavioural aggregation. A single aggregate probability distribution synthesises the opinions, knowledge and beliefs of separate experts. This method is also referred to as mathematical aggregation or pooling (O'hagan, 2019). Behavioural aggregation asks groups of experts to discuss their opinion and knowledge, which leads to judgements as a group (Krueger et al., 2012). One of the benefits of single aggregation above behavioural aggregation is that more junior or introvert experts may express their knowledge modestly. In contrast, more senior or extrovert experts may dominate the group discussion. Also, there is a risk of group thinking. Group thinking is a tendency for a debate to be limited to perceptions and topics that will be broadly acceptable to all members of the group. The risks of the single aggregation are that it requires choices of a mathematical formula also called "pooling rules" to aggregate the expert distributions. The structured expert elicitation of this study uses single aggregation to avoid group thinking and dominant group members. It will illustrate the results of different pooling rules to mitigate the risk of individual preferences for specific pooling rules.

Bayesian aggregation methods
One of the single aggregation approaches is based on Bayesian' theorem. In Bayesian interference, the probability of a hypothesis being true conditional on the sample data is investigated. This hypothesis involves a model with unknown or known parameters. This probability can be found using Bayes' Theorem (Bayes, 1763), given in equation 4.1 (Ellison, 2004). This equation represents the consequence of learning from an experience where an initial state of knowledge is renewed to a new state of knowledge (O'Hagan et al., 2006).

$$f(\theta|D) = \frac{f(D|\theta)\cdot f(\theta)}{f(D)} \tag{4.1}$$

- The elicitation process elicits the beliefs of θ for expert i as the distribution of $f_i(\theta)$. $D = \{f_1(\theta),...,f_n(\theta)\}$ represents the set of experts' elicited distributions;
- $f(D|\theta)$ represents the prior beliefs of the decision-maker of what the experts are going to tell them, conditional on the true value of θ;
- The decision-maker is ultimately interested in the unknown quantity of θ and would like to incorporate the opinion and beliefs of n experts ultimately leading to f(θ|D);

However, even in the simplest case, when there are only two experts involved, this process is difficult. The decision-maker has to elicit its own prior distribution f(θ) for θ and also, his beliefs about what the experts are going to tell him, conditional on the true value of θ. This problem is addressed by different researchers to simply these tasks, but it remains a complex task which is difficult to implement (Soares et al., 2011). It gives a heavy burden on the decision-maker (Cooke et al., 1991).

Pooling
In pooling methods, the aggregation of distribution is defined as a function of the different elicitations. The distributions of the different experts are combined, using a certain weighting for each expert. The weighing can be taken as equal, based on certain criteria, on some Laplacian Principle of Indifference, or of equity. In the mid-1980s, Cooke et al. (1991) developed a method of linear pooling, called *The Classical model* that combines expert judgment based on their performance on a calibration set (questions where only the assessor knows the answers of) of uncertainties. The method of Cooke is the most frequently applied method of all expert judgments. A risk of this method is that the calibration set has to reflect well the domain that covers the important variables. However, most likely the expert seeks the advice of experts in the areas where past data is rare which makes it is difficult to generate a subjective calibration set, which has uncontested answers.

4.2.2. Evaluating the survey responses via the Classical Model

Because of the above-mentioned difficulties regarding the Bayesian method, the method of the "Classical model" evaluates the results of the questionnaire. The questionnaire consists of seed questions (questions we know the answers of) and questions of interest (questions where we would like to know the answer of). This method applies performance-based average weighting, where each expert obtains a certain weight depending on his or her performance on the seed questions. To capture the subjective uncertainty of expert, all questions require answers in a probabilistic form.

Weighting scores from seed questions
Each expert receives a weighting from his or her performance on the seed questions (questions we know the answers of). The weighting is calculated with the calibration and information scores. A high weighting score indicates that the expert knows a lot about the topic and will, therefore, have more influence on the results than experts that know little or less about a topic. The normalised weighting score for expert e is calculated as follows:

$$w_\alpha(e) = \frac{C(e)\cdot I(e)\cdot I_\alpha(C(e))}{\sum_e w_e}, \tag{4.2}$$

where

$$I_\alpha(C(e)) \begin{cases} 0, & \text{if } x \le \alpha \\ 1, & \text{otherwise.} \end{cases}$$

C(e) is the calibration score, *I(e)* is the information score, $I_\alpha(C(e))$ is the indicator function and *e = 1,.., E* represents the set of experts (Cooke and Goossens, 2004). α is a certain threshold, chosen to maximise the combined score of the resulting decision-maker. The combination of the quantiles of the expert's assessment and the weighting scores determines the decision maker's outcome.

Calibration score
The calibration score measures the differences between the expected and the true proportion of realisation in each interval. Each expert gives its best (median), a minimum and a maximum estimate of realisation X for each question *i.* The best estimate is presumed to be the 50-percentile. For most experts, the verbalised minimum is not their absolute minimum, but rather a value close to their 5-percentile. This theory also applies for the maximum and the 95-percentile. The minimum and maximum values are adjusted according to this theory which generates a more conservative and hence wider interval (Benini, 2017), (Greenberg, 2013), (O'Hagan and Oakley, 2004). In that manner, the experts divide its assessment into four inter-quantile ranges. The inter-quantile ranges define the theoretical probability vector *P*, where:

- $p_1 = 0.05$: the probability that X is smaller or equal than the 0.05 probability;
- $p_2 = 0.45$: the probability that X is larger than 5-quantile and smaller than the 50-quantile;
- $p_3 = 0.45$: the probability that X is larger than the 50-quantile and smaller than the 95-quantile; and
- $p_4 = 0.05$: the probability that X is larger than the 95-quantile.

In practice, experts' inter-quantile ranges do not usually capture the true realisations at the expected frequency. The actual realisation given in vector *S* shows the observed proportion of realisation $S = (s_1, s_2, s_3, s_4)$. The difference between the true realisation and the expected realisations leads to the statistical accuracy or calibration score. The Kullback-Leibler divergence calculates the differences between the two distributions (equation 4.3), with *n* for each quantile range.

$$I(S,P) = \sum_{i=1}^{n} S(i) \ln \frac{S(i)}{P(i)} \tag{4.3}$$

$$H_0 := \text{the uncertain quantities are independent and identically distributed with distribution P}$$

H_0 is interpreted in this theory as the probability, under H_0, of observing a difference in a sample distribution S' at least as large as I(S,P), on *n* observations. The theory follows a $2nI(S,P) \sim \chi^2_3$ distribution. Equation 4.4 leads to the calibration score for a given expert *e.* Where F is the cumulative distribution function of the χ^2 random variable with *m* number of calibration questions and 3 degrees of freedom. A calibration score is a number between 0 and 1, where a higher calibration score indicates a higher statistical accuracy. A software package *Excalibur v1.5.7 Pro* (LightTwist Software, 2013) calculates the calibrations (Nane, 2020).

$$C(e) = 1 - F(2mI(S,P)) \tag{4.4}$$

Information score
The information score indicates the width of the confidence interval and shows the concentration of the distribution. The informative score is relative to a standard uniform background distribution.

Every question has an informative score, which considers all experts' assessment. First, equation 4.5 calculates the intrinsic range with a ten per cent overshoot range. Where L is the minimum of all experts assessment, including the realisation and U is the maximum of all expert assessment including the realisation.

$$[L^*, U^*] = [L - \frac{1}{10}(U-L), U + \frac{1}{10} * (U-L)] \tag{4.5}$$

Equation 4.6 calculates the informative score for expert e for one question and equation 4.7 calculate the final information scores, taking all questions into account.

$$I(e) = p_1 \ln \frac{p_1}{q_5 - L^*} + p_2 \ln \frac{p2}{q_{50} - q_5} + p_3 \ln \frac{p2}{q_{95} - q_{50}} + p_4 \ln \frac{p_4}{U^* - q_95} + \ln\left(U^* - L^*\right) \tag{4.6}$$

$$I(e) = \frac{\sum_{J=1}^{M} I_j(e)}{M} \tag{4.7}$$

Decision maker

The combination of the expert assessments and the weighting scores lead to the *virtual expert* or so-called *the decision-maker*. This decision-maker represents a mathematically calculated distribution which corresponds to a virtual expert. The decision-maker will perform better than all other experts (Cooke and Goossens, 2008) and the results of the decision-maker will be adopted.

The results of the calibration and information scores for N experts reward good expertise and passes these virtues on to the decision-maker. The Classical Model contains three different weighting schemes for aggregating the distribution elicited from the experts: equal weighting, global weighting, and item weighting. These different weighting systems differ in the method where each expert receives his or her weight. With equal weighting, each expert gets the same weight. Global and item weighting schemes are performance-based weighting systems and are based upon the experts' performance in the calibration and information score.

$$DM_\alpha(i) = \frac{\sum\limits_{e=1,\ldots,E} w_\alpha(e) f_{e,i}}{\sum\limits_{e=1,\ldots,E} w_\alpha(e)} \tag{4.8}$$

With the global scheme, the information score is based on all the assessed seed items. The global weight DM_α (equation 4.8) is DM_{α^*} where α^* maximised the calibration score and information score and f_e, i is expert e's density for question i and w_α(e) given in equation 4.2. The weight is global because the combination of all assessed seed items determines the information score.

The item weighting is different because it uses a different set of weight for each time rather than the average information score, shown in equation 4.9. The item weight DM is DM_α, where α^* maximised the product of the calibration and information score. The benefits of item weighting are that experts can up or down weight themselves when they know more or less about a specific topic. Knowing more about a particular topic means choosing percentiles that are closer to each other.

$$w_\alpha(e,i) = 1_\alpha \cdot C(e) \cdot I(f_{e,i}|g_i) \tag{4.9}$$

For each α, the item weight DM_α of item i as:

$$IDM_\alpha(i) = \frac{\sum\limits_{e=1,\ldots,E} w_\alpha(e,i) f_{e,i}}{\sum\limits_{e=1,\ldots,E} w_\alpha(e,i)} \tag{4.10}$$

There is not mathematically theorem that suggest that either item weights or global weights outperform equal weighting. In practice, global weights are used unless item weight performs markedly better.

4.2.3. Software settings

This section explains briefly the software settings that are used to calculate the experts' performance with the Excalibur software package (LightTwist Software, 2013). The use of the software requires settings that are selected according to the Classical model. Excalibur performs a formula that is a little different than the calibration score (equation 4.11). The power value is chosen to be 1 so that the formula corresponds to the calibration score (equation 4.4).

$$C(e) = 1 - \chi^2 \cdot 2\text{mI (S,P)} \cdot \text{power} \tag{4.11}$$

As explained in chapter 4.2.2, in order to acquire a minimally informative distribution, the intrinsic range is set to 0.1, corresponding to the "10% overshoot" rule. The significance level, α, or "threshold" is tested with 0 and 0.05. With the value of 0.00, all experts are taken into account. In hypothesis testing, a significance level of 0.05 is a commonly used value.

4.3. Results

4.3.1. Expert respondents

The survey was shared with the Sustainable Sanitation Alliance. This is a network of individuals and partners that are making an effort to achieving the SDGs related to sanitation systems. The survey is also shared with sanitation experts from the Bill & Melinda Gates Foundation. In total, nineteen experts responded to the survey. In the survey, the respondent had the option to give more information about their background and experience with sanitation. Eight of the nineteen respondent gave more information about their background, shown in table 4.3. Eight of the nine experts indicated more than ten years of experience with sanitation. Also, six of the nine experts emphasised his or her international experience. Appendix B.3 shows extra comments that were given after each question.

Table 4.3: Background information indicated by experts

Expert #	Information
4	Process engineer with more than ten years of experience in WASH.
5	Sanitary engineer with more than fifteen years of international experience.
7	Public health Engineer with over ten years of experience in Urban Africa and South Asia.
8	Sanitary engineering with 27 years of sanitation and environmental health experience around the world (Philippines, Vietnam, Cambodia, Thailand, Sri Lanka, China, Mexico, Guatemala, El Salvador, Honduras, Indonesia, Bhutan and Nepal)
10	Sanitation specialist that worked in Tanzania, Zambia, Rwanda, Ghana, Ethiopia, Zimbabwe, Kenya for more than 50 years.
11	Wash technical officer in Cambodia with an Msc. in Environmental Engineering
12	Senior Technical Advisor in WASH in India who has worked with WASH for fifteen years.
13	Wash engineer that worked in Senegal, Togo, South Africa, Haiti, Peru and Colombia for more than ten years.
19	Independent water and sanitation specialist that works on design, implementation and evaluation of WASH programmes in Asia and Africa and has more than 40 years of experience.

4.3.2. Performance of experts

The subsequent section shows the performance of the thirteen experts with aggregation settings of the software package Excalibur. The underneath text box summarises some of the key concepts and terms of this analysis.

Keyterms and definitions in section 4.3.2 regarding expert elicitation

- **Basic settings:** the aggregation of the experts (or virtual decision-maker) includes all performances of the experts
- **Basic settings with $\alpha = 0.05$:** the aggregation of the experts (or virtual decision-maker) includes only the experts that scored a calibration score > 0.05
- **Basic settings optimized:** the aggregation of the experts (or virtual decision-maker) chooses a value for α which optimizes the calibration score of the decision-maker
- **Equal weighting:** the aggregation of the experts (or virtual decision maker) uses an equal weighting for all experts
- **Total mean relative information score:** average information score over all questions including the questions or interests
- **Mean relative information score:** average information score only over the calibration questions

Basic setting

Table 4.4 shows the performance of the thirteen experts with basic settings. Expert 1, 5, 10, 11, 15 and 18 did not complete the survey and were excluded from the analysis. The table indicates that expert 3, 6 and 8 are very well-calibrated. The information scores for all experts are high. The most informative expert (expert 4) shows the second-lowest calibration score. Because expert 3, 6 and 8 have a high calibration score, they also received the highest weights. Expert 8 gave extra information about his or her background and indicates that he/she has more than 27 years of experience in sanitation and environmental health in many countries around the world, which reflects also the high calibration score.

Basic setting with a significance level of 0.05
Table 4.5 shows the expert performance with the significance level of 0.05. Because of the thresholds, all calibration scores with a value lower than 0.05 did not receive a weight. This is the case for expert 4, 12, 14 and 16. From these experts, experts 4 and 12 additional information about their experts. They both indicated experience with sanitation of more than ten and fifteen years respectively. This seems high. However, the experts that scored high and also gave additional information had 27 years of experience. Compared to the results of the basic settings, shown in table 4.4, the normalised weights of the experts that did receive a weighting were are bit higher because fewer experts are included.

Basic settings optimized
In the software of Excalibur, there is an option "DM (decision-maker) optimisation". This option chooses a significance level for which the global unnormalised weight of the decision-maker is maximal, and hence this virtual expert performs better than all other experts when considering both the calibration and information score. The optimised options show that with a threshold of 0.147, the results of the decision-maker are optimal. The performance of many experts is excluded; the values of expert 4, 7, 9, 12, 13, 14 and 16 is not included (table 4.6). Expert 4, Expert 6 and Expert 8 receive the highest weights. Expert 8 (with the best weight) is also the expert that indicated that he or she have had 27 years of worldwide experience in sanitation and environmental health. Expert 4 and 6 did not give any additional information regarding their experience with sanitation. This weighting scheme leads to a higher calibration and information score for the decision-maker than the previous settings.

Table 4.4: Expert performances with α is 0. Expert 3, 6 and 8 received the highest weighting scores. Expert 12 the lowest.

	Calibration	Mean relative information		Unnormalized weight	Normalized weight	
		Total	Realization		Without DM	With DM
Expert 2	0.15	1.27	1.18	0.17	0.04	0.03
Expert 3	**0.46**	1.63	2.09	0.96	**0.24**	0.20
Expert 4	0.02	2.20	3.30	0.07	0.02	0.01
Expert 6	**0.46**	1.58	1.48	0.68	**0.17**	0.14
Expert 7	0.07	1.26	2.44	0.18	0.04	0.04
Expert 8	**0.46**	2.01	2.51	1.15	**0.29**	0.24
Expert 9	0.07	1.47	1.29	0.09	0.02	0.02
Expert 12	0.00	1.76	2.62	0.01	0.00	0.00
Expert 13	0.07	1.76	1.80	0.13	0.03	0.03
Expert 14	0.00	0.89	1.97	0.01	0.00	0.00
Expert 16	0.00	2.24	3.44	0.07	0.02	0.02
Expert 17	0.15	1.64	2.13	0.31	0.08	0.07
Expert 19	0.15	1.27	1.18	0.17	0.04	0.04
Decision maker	**0.81**	0.68	**0.96**	0.78		0.16

Table 4.5: With an α of 0.05 expert 12 and 16 do not receive a weighting. The calibration and informative score is equal

	Calibration	Mean relative information		Unnormalized weight	Normalized weight	
		Total	Realization		Without DM	With DM
Expert 2	0.15	1.27	1.18	0.17	0.05	0.04
Expert 3	0.46	1.63	2.09	0.96	0.25	0.21
Expert 4	0.02	2.20	3.30	0.00	0.00	0.00
Expert 6	0.46	1.58	1.48	0.68	0.18	0.14
Expert 7	0.07	1.26	2.44	0.18	0.05	0.04
Expert 8	0.46	2.01	2.51	1.15	0.30	0.25
Expert 9	0.07	1.47	1.29	0.09	0.02	0.02
Expert 12	**0.00**	1.76	2.62	0.00	**0.00**	0.00
Expert 13	0.07	1.76	1.80	0.13	0.03	0.03
Expert 14	0.00	0.89	1.97	0.00	0.00	0.00
Expert 16	**0.00**	2.24	3.44	0.00	**0.00**	0.00
Expert 17	0.15	1.64	2.13	0.31	0.08	0.07
Expert 19	0.15	1.27	1.18	0.17	0.05	0.04
Decision maker	**0.81**	0.68	**0.96**	0.78		**0.17**

Equal weighting system
Table 4.7 shows the expert performance with equal weighting. There are no thresholds, therefore all the expert receive a weighting. Since there are thirteen experts, all experts receive a weight of 0.077. The calibration score of the decision-maker is still relatively high. However, the decision-maker has an information score that

Table 4.6: An optimized α leads to exclusion of expert 4, 12, 14 and 16. Expert 3, 6 and 8 dominate the results for the decision maker. The calibration and information score is higher than in the previous settings

	Calibration	Mean relative information		Unnormalized weight	Normalized weight	
		Total	Realization		Without DM	With DM
Expert 2	0.15	1.27	1.18	0.17	0.05	0.04
Expert 3	0.46	1.63	2.09	0.96	**0.28**	0.22
Expert 4	0.02	2.20	3.30	0.00	0.00	0.00
Expert 6	0.46	1.58	1.48	0.68	**0.20**	0.16
Expert 7	0.07	1.26	2.44	0.18	0.00	0.00
Expert 8	0.46	2.01	2.51	1.15	**0.33**	0.27
Expert 9	0.07	1.47	1.29	0.09	0.00	0.00
Expert 12	0.00	1.76	2.62	0.00	0.00	0.00
Expert 13	0.07	1.76	1.80	0.13	0.00	0.00
Expert 14	0.00	0.89	1.97	0.00	0.00	0.00
Expert 16	0.00	2.24	3.44	0.00	0.00	0.00
Expert 17	0.15	1.64	2.13	0.31	0.09	0.07
Expert 19	0.15	1.27	1.18	0.17	0.05	0.04
Decision maker	**0.81**	0.95	**1.09**	0.88		0.20

Table 4.7: Expert performances with equal weighting

	Calibration	Mean relative information		Unnormalized weight	Normalized weight	
		Total	Realization		Without DM	With DM
Expert 2	0.15	1.27	1.18	0.17	**0.077**	0.04
Expert 3	0.46	1.63	2.09	0.96	**0.077**	0.21
Expert 4	0.02	2.20	3.30	0.07	**0.077**	0.02
Expert 6	0.46	1.58	1.48	0.68	**0.077**	0.15
Expert 7	0.07	1.26	2.44	0.18	**0.077**	0.04
Expert 8	0.46	2.01	2.51	1.15	**0.077**	0.25
Expert 9	0.07	1.47	1.29	0.09	**0.077**	0.02
Expert 12	0.00	1.76	2.62	0.00	**0.077**	0.00
Expert 13	0.07	1.76	1.80	0.13	**0.077**	0.03
Expert 14	0.00	0.89	1.97	0.01	**0.077**	0.00
Expert 16	0.00	2.24	3.44	0.07	**0.077**	0.02
Expert 17	0.15	1.64	2.13	0.31	**0.077**	0.07
Expert 19	0.15	1.27	1.18	0.17	**0.077**	0.04
Decision maker	**0.81**	0.68	**0.96**	0.78		0.14

is significantly lower than with the global weighting scheme with a significance level of 0.147.

Comparing the high priority hazardous event with equal weighting and optimized weighting
Table 4.8 and 4.9 show the outcome of the decision-makers risk estimates. The outcome shows similar patterns. For the best estimate scores, surface flooding, groundwater pollution and local watercourse pollution show for both weighting schemes the highest risks. The priority ranges are larger with the optimized weighting scheme than with the equal weighting scheme. This is probably because experts with low calibration scores, that also indicated large ranges, were excluded from the optimized weighting schema and were included in the equal weighting schema.

Table 4.8: Estimated risks for each hazardous event with optimized weighting scheme

	Risk score		
	p = 0.05	*p=0.50*	*p = 0.95*
Hazardous event			
Groundwater pollution	4	15	46
Local water course pollution	3	16	46
Backing-up of sewage	1	8	31
Solids discharged from tank	2	10	20
Surface flooding	6	21	37
Odours	1	4	24
Tank full/tank lifts	2	10	32

Table 4.9: Estimated risks for each hazardous event with equal weighting

	Risk score		
	p = 0.05	*p=0.50*	*p = 0.95*
Hazardous event			
Groundwater pollution	3	21	74
Local water course pollution	2	18	67
Backing-up of sewage	1	10	72
Solids discharged from tank	1	11	72
Surface flooding	3	23	75
Odours	1	5	47
Tank full/tank lifts	1	15	68

	Low risk	*Medium risk*	*High risk*	*Very high risk*
Risk score	<6	6 -12	12-32	32<

4.3.3. Relevance of required emptying frequency

The best estimates show that groundwater pollution, local watercourse pollution and surface flooding have the highest risks (table 4.8). Where surface flooding has the highest risks. Each of the three hazardous events has causes that can be mitigated by periodically emptying. Appendix C shows the connection between hazardous events, causes of hazardous events and mitigating measures. In the additional comments, expert 6 (who also received a high calibration score) added to the hazardous event of Discharge of solids that "Discharge of solids will lead to the leach field failing and therefore flooding out of the tank or waste on the ground surface. Therefore risk levels remain high".

Giving users or policymakers a required emptying frequency and under the assumption that users would follow the recommended emptying frequency, will decrease the occurrence of the three hazardous events and will decrease their risk.

4.3.4. Useful insight from additional comments from experts

After each question, the experts had the option to provide additional comments or information. In this section, the comments are summarized. Appendix B.3 shows the full list. Concerning groundwater pollution, Expert 7 emphasized the importance of good constructions and maintenance of the septic tank and the leach field. If the construction and maintenance are carefully done, the risks are negligible. If not, then the risks can be very high and could contribute to a health outbreak. Expert 10 and 16, indicated that the health effects are highly influenced by the location of the water supply. Regarding the backing-up of sewage, expert 13 explained that when these hazardous events happen, people tend to clean up raw waste relatively soon. Expert 10 indicated also, that if people are aware of the health risks dealing with the mess, the risks are low. Expert 10 also mentioned that he had lived for almost 30 years with septic tanks in Africa and that during that time, this event happened three times. Expert 6 has a high calibration score and comments about the discharge of solids that the discharge of solids will lead to a leach field that fails and that therefore the waste will flood out of the tank to the ground surface. Finally, expert 10 had experience in Germany with a lifting tank. He explained that a plastic that is filled with groundwater will lift and the system will back-up of overflow, depending on the elevation of the toilet.

4.4. Conclusion

The structured expert judgment may offer a reliable manner to prioritise different risks of OSS systems and assess the relevance of specific solutions. This expert judgment aimed to assess the impact of a recommended emptying frequency to overcome the problem that OSS systems are emptied too late and are thus overflowing. Or, when a tank is emptied on the recommended time but is still not full enough, this could indicate that the tank is in fact leaking.

To scrutinize the knowledge of the experts, a structured expert judgment is used. Subsequently, the performance of experts is aggregated with different weighting schemes, which created a virtual expert. The virtual expert was able to create results with high calibration scores in both the equal weighting system and in the optimized weighting system. In both the weighting systems, the virtual expert allocated three high-risk hazardous events: groundwater pollution, local watercourse pollution and surface flooding. Periodically emptying can mitigate and impact all of these three high-risk hazardous events and would, therefore, be a useful solution.

5

Modelling a recommended emptying frequency

Abstract

Objectives
The performance and safety of septic tanks are dependent on the fullness of a septic tank. However, scientists have not found a simple method which makes it accessible to determine how fast a septic tank fills and how often a tank should be emptied. The fill rate of septic tanks depends on the accumulation of sludge and is controlled by a number of factors. The in-field measurements of all of these factors are expensive, complicated and unfeasible. This study aims to simulate the fill rate of a septic tank as accurate as possible using the least possible in-field measurements which can lead to relevant recommendations of emptying frequencies that are easily accessible by tank owners or tank managers, policymakers or regulators.

Method
A numerical model is developed which can simulate the fill rate/sludge accumulation in septic tanks. A sensitivity analysis shows what characteristics of the septic tank or sludge inside the tank are sensitive for the results of the model and need careful in-field measurements to generate accurate results from the model. The characteristics that are less sensitive or influential for the results are approximated with default values which are found through a GLUE method that uses multiple Monte Carlo simulations. Ultimately, by using the model, the approximated non-key-parameter values and different values for the key-parameters, recommended emptying frequencies can be calculated. A user-tool is developed with a method from Sage and Armstrong Jr (2000) to translate the results of the model, to tank owners or managers, policy-makers or regulators in a simple manner.

Results
The sludge accumulation depends on ten parameters. The sensitivity analysis shows that the variance of the sludge accumulation is mostly associated with the water content and specific gravity variance. The calculated distributions for the default values show similar patterns to the values obtained from a literature review. The numerical model simulates the performance of the septic tank with a correlation value of 0.98 and 0.9, compared to the values identified in the literature review. The calculated emptying frequencies range between 2 and 26 years depending on the water content, the specific gravity of sludge, amount of users and applied guidelines. To make the results as accessible as possible, a user-tool is developed that provides personalized recommendations, based on the outcome of the model, easily.

Conclusions
The simulation of the numerical model shows a high correlation with the values found in literature and can generate recommendations for emptying frequencies. The water content and specific gravity of sludge are identified key-parameters because of their high sensitivity to the results of the model. The GLUE method estimates default values for the eight non-key parameters. The developed user tool makes the outcome of the model accessible for different kind of users.

5.1. Introduction

The ultimate goal of the model is to gain knowledge of the safety or status of a specific tank, on a specific location, used by a specific amount of people, with only a couple in-field measurements. The performance and safety of septic tanks are highly dependent on the fullness of the septic tank which is controlled by the fill or accumulation rate of sludge (Al Momani, 2015). However, scientists have not found a simple method which makes it accessible to determine the accumulation rate (Appendix A). Knowing the sludge accumulation rate and therefore, knowing how fast a tank fills, can provide approximations on the necessary time between two emptying events or, with other words, the emptying frequency.

The accumulation of sludge depends upon a wide range of factors (chapter 2.4). The in-field measurements of all of these factors are expensive, complicated and unfeasible. This study aims to simulate the accumulation of sludge inside a septic tank as accurate as possible using the least possible in-field measurements. To make sure that future users apply the model in a correct and relevant manner, the decisions that were made during the modelling processes are explained in details in Appendix E.

The data of emptying frequencies are often acquired during household surveys or census (UNICEF and WHO, 2019). The similarities or discrepancies between the data acquired from census or household surveys and the calculated necessary emptying frequency enables to estimate whether a septic tank is safe or not. These estimations could create a global overview of the status of OSS systems which leads to a more targeted solution to achieve safe sanitation. Secondly, knowing the required emptying frequencies could help policy-makers to formulate recommendations and guidelines for safe operations and safe maintenance of septic tanks, which can stimulate and facilitate users to adopt these recommendations.

5.2. Intended users of the model

Given the above stated current acknowledge difficulties in the current emptying frequencies, there are three different intended users of the model:

- a manager or owner of a septic tank who would like to know when to empty his or her tank based on a small number of measurements;
- a policymaker who is likely to set standards, guidelines or regulations on emptying frequency by including data on their typical conditions in the jurisdictions of his or her region (e.g. size of the tank, the degree of water content);
- a regulator who would like to get insight into the safety of his or her (national) septic tanks and would like to compare the data on the actual emptying frequency with the calculated emptying frequency.

5.3. Overview of the model

Figure 5.1 summarises the steps of the model. This brief section gives an overview of the different steps of the model. The subsequent sections will explain each section in more details. The modelling choices are explained in more details in Appendix E.

Core of the model: numerical sludge accumulation equation

The core of the model is a numerical equation based on a mass balance that approximates the volume of sludge in a septic tank over time. The model needs ten input parameters to describe the characteristics of the septic tank and the faecal matter entering into the systems. Section 5.4.1 explains the theory and background of the numerical equation .

Analyze sensitivity parameters

The start (indicated in the colour teal of figure 5.1) analyses the sensitivity of all parameters of the sludge accumulation and makes a distinction between key-parameters and non-key parameters. The key-parameters are the ones that have a significant influence on the output of the model and need in-field measurements in order to get an accurate result of the volume of sludge accumulation. The non-key parameters are the parameters that are not very sensitive and will not have a significant influence on the output of the model. The non-key parameter will receive default values. Measuring only the key-parameters is a more cost and time-efficient manner which will still lead to accurate results. Section 5.5.1 explains the theory and applied methods of the sensitivity analysis in more details.

First iteration: generate N parameter sets from uniform distribution
The first iterations over the first three blue boxes of figure 5.1 will create default values for the non-key parameters. The model starts with uniform distributions of each parameter based on boundary conditions found in the literature. In the first iteration, the model draws N random parameter sets from the uniform distributions of the non-key parameters. With each (non-key) parameter set a volume of sludge accumulation is calculated (second blue box of figure 5.1), which subsequently is compared to the volumes of sludge accumulation found in the literature. The distribution of the 0.1% parameter sets that score most similarities are saved and used for the second iterations. Section 5.4.3 explains more in-depth the details of this method.

Second iteration: generate N parameter sets from calculated distribution
The second iteration starts again at the top blue box and draws N parameter sets from the calculated parameter distributions. For each parameter set, the volume of sludge accumulation is calculated over time (second blue box in figure 5.1). Subsequently, the calculated volumes of sludge accumulation are compared to the sludge accumulation found in the literature (third blue box in figure 5.1). The distribution of the 0.1% parameter sets that show most similarities are saved and further analysed. From that last set, the 50-percentile values of each parameter distribution remain. Section 5.4.3 explains more in-depth the details of this method.

Third iteration: Calculate emptying frequencies
With the calculated 50-percentiles values for the non-key parameters and the in-field measurements from the key parameter, the model calculates the volume of sludge accumulation in septic tanks. Finally, the emptying frequency of septic tank is determined as indicated in the last black box of figure 5.1. Section 5.4.3 explains more in-depth the details of this method.

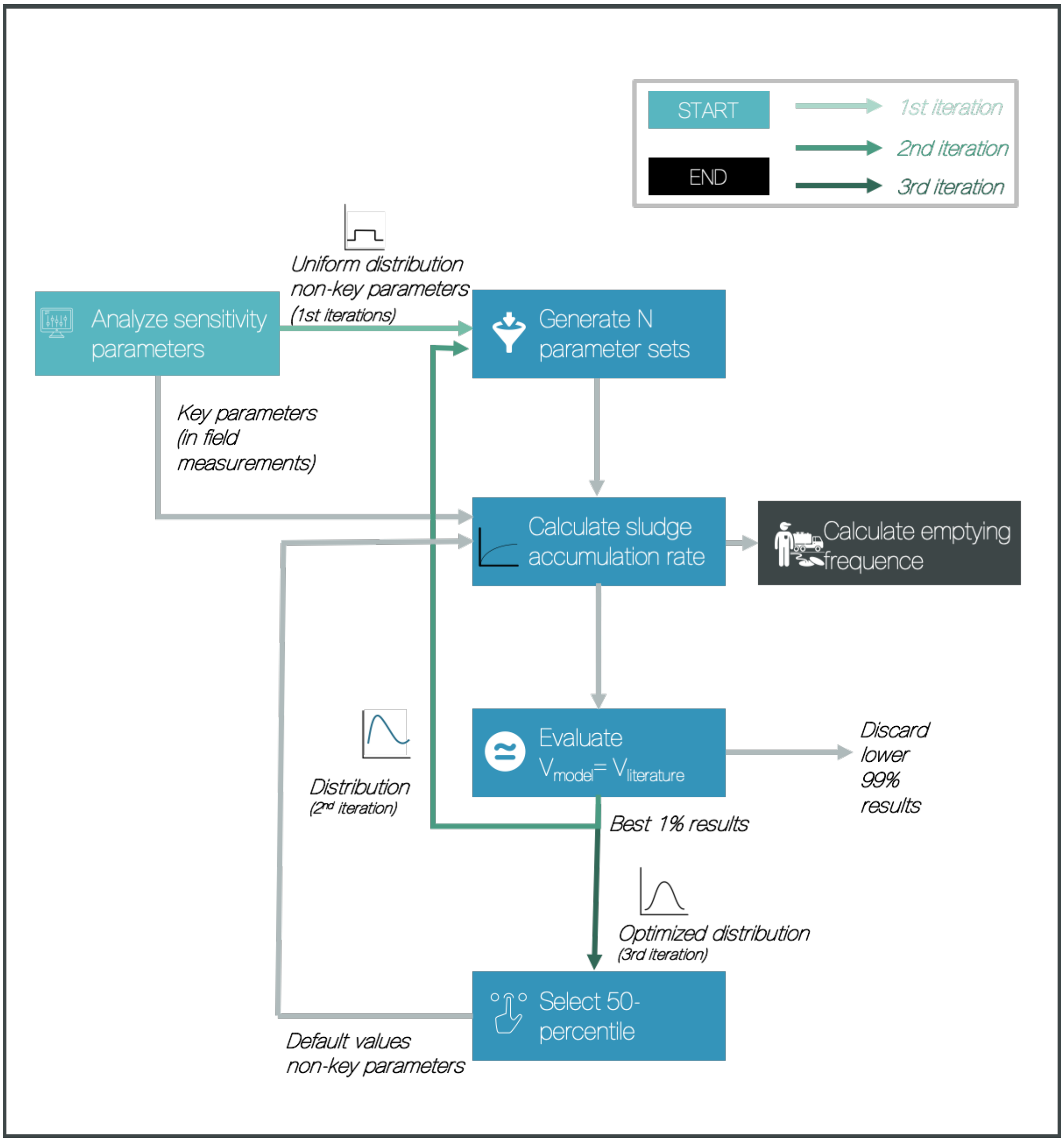

Figure 5.1: Schematic overview of the model steps

5.4. Method: developing a model

5.4.1. Simulating the accumulation of sludge

The model applies the mathematical sludge accumulation equation of Al Momani (2015). The performance of this equation shows a correlation coefficient of more than 0.88 with the empirical models of Weibel (1995) and Bounds (1995). The parameters of the model are inherent properties of the solids and tank and are assumed constant in time for the modelled period. The basis of the mathematical equation is a general mass balance, which assumes a constant inflow of mass into the tank and a variable outflow. The model approaches the difference of solid mass in the tank or accumulation of solids inside the tank as follows:

Mass of solids in the inlet of the tank
- Mass of solids at the effluent of the tank
- Mass of solids decomposed anaerobically
+ Mass of solids generated by bacterial growth

Mass of accumulated solids in the septic tank

$$\frac{dM}{dT} = QC_0 - QC_e(t) - k\Delta M + Yk\Delta M \tag{5.1}$$

Equation 5.1 calculates the change in mass at time step t. M is the mass of accumulated settleable solids in the tank at time step t and Q is the flow rate of raw sewage to the tank in m^3/year. C_0 and C_e are the influent and effluent concentration of settleable solids in kg/m^3 respectively. ΔM is the mass of solids composed through anaerobic processes in kg, and Y is biological yield coefficient (kg/kg), k is an organic matter biodegradation rate constant per year.

Al Momani (2015) integrates equation 5.1 to equation 5.2. Where χ is the nonbiodegradable part of the solids (-), A is the surface area of the septic tank in m^2, h_e is height of the effluent line in m, η is calculated with $\frac{C_0-C_e}{C_0}$ (-) and θ_i is the initial detention time. β is calculated with equation 5.3. γ it slope between sludge accumulation and solids removal efficiency (kg).

$$M = C_0Q\chi t + C_0(Ah_e) + \frac{Q\eta}{\beta}C_0(\frac{e^{\beta t}}{e^{\beta\theta_i}} - 1) \tag{5.2}$$

$$\beta = \frac{QC_O}{\gamma}(k - YK - 1) \tag{5.3}$$

Equation 5.2 converts the mass of settleable solids in the tank to the volume with the density of the sludge. Where SG represents the specific gravity of solids or sludge (−) and w = water content of settleable solids (−). Appendix D shows the integration of formula 5.2, as given in the article of Al Momani (2015).

$$V_{\text{sludge}} = \frac{C_0Q\chi t + C_0(Ah_e) + \frac{Q\eta}{\beta}C_0(\frac{e^{\beta t}}{e^{\beta\theta_i}} - 1)}{1000SG(1-w)} \tag{5.4}$$

5.4.2. Identification of key parameters with sensitivity analyses

Simulating the accumulation of sludge with equation 5.4 would generally involve a large number of in-field measurements for each parameter by the user of the model. However, this is often expensive and unpractical. Instead, it is more efficient to measure only the parameters that have the largest influence on the accumulation of sludge, which can be done with a sensitivity analysis. The objective of the sensitivity analysis is to illustrate how uncertainty in the output of the model apportions to different sources of uncertainty in the model input. In that manner, the key parameters can be used as specific values for a specific assessment of a tank, whereas for the other parameters, the model uses default values. Also, this analysis identifies where data acquiring and future investigations are most likely to have the most significant impact. Table 5.2 show the initial values of the parameters with the corresponding sources of literature. Commercially available tanks determined the tank specific values, indicated in table 5.1.

Table 5.1: The initial parameter ranges/values derived from literature

Parameter	Symbol	Range/ value from literature	Unit	Source	Boundary conditions
Influent concentration of settleable solids	C_0	0.084-0.33	(kg/m^3)	Chaffee (2008) USEPA (2005)	$0 \leq C_0 \leq 1$
Effluent concentration of settleable solids	C_e	0.002-0.149	(kg/m^3)	Chaffee (2008), USEPA (2005)	$0 \leq C_e \leq 1$
Fraction of solids that are non-biodegradable	χ	0.1-0.15	(-)	Agunwamba (2001), Nnaji and Agunwamba (2012)	$0 \leq \chi \leq 1$
Specific gravity of sludge	SG	1.03	(-)	Saqqar and Pescod (1995)	(-)
Water content of sludge	w	0.88	(-)	Saqqar and Pescod (1995)	(-)

Table 5.2: Minimum and maximum tank values based on commercially available tanks

Parameter	Symbol	Range	Unit	Source	Boundary conditions
Surface area of the tank	A	1.5 - 25	(m^2)	*plastic-mart.com* *tank-depot.com* *theseptictankstore.com*	$A \leq 40$
Raw sewage flow rate to the tank	Q	45-55	(m^3/person /day)	Strande et al. (2020) *tank-depot.com*	$Q \leq 400$
Height of the tank	h	1.4-3 m	(m)	*plastic-mart.com* *tank-depot.com* *theseptictankstore.com*	$h \leq 8.5$

Local sensitivity analysis
A local sensitivity analysis measures how small perturbations of one input value change the results of the output. This classic approach is called the One factor At a Time (OAT) method and measures the variation of the output by changing one factor (Campolongo et al., 2007).

Global Sensitivity analysis of Sobol
Sobol (2001) uses a method that quantifies the interaction of two or more parameters on the variance of the output in a global sensitivity analysis. Compared to the local sensitivity analysis, the global sensitivity analysis is more realistic since the input parameters can be varied simultaneously.

Sobol' method estimates the effect of every single input parameter to the complete variance of the output. The research obtains two Sobol' indices:

- first-order Sobol' index S_n: calculation of the impact of each parameter by estimating the partial variance of Y. The variance of the response is reduced, while the parameter is fixed. It measures the contribution of every parameter, without interactions with others, to the total variance of the output, e.g. when the reduction of the variance is substantial, the parameter is considered very sensitive; and

- total effect index S_{T_n}: the total contribution, including the interaction with other parameters, to the response variance (equation 5.5). The equation is further explained in the next section.

$$S_{T_n} = S_n + \sum_{n \leq n'} S_{n,n'} + \sum_{n' \neq n, n'' \neq n, n' \leq n''} S_{n,n',n''} + ... \tag{5.5}$$

The results of both analyses lead to the key-parameters of the sludge accumulation model and need in-field

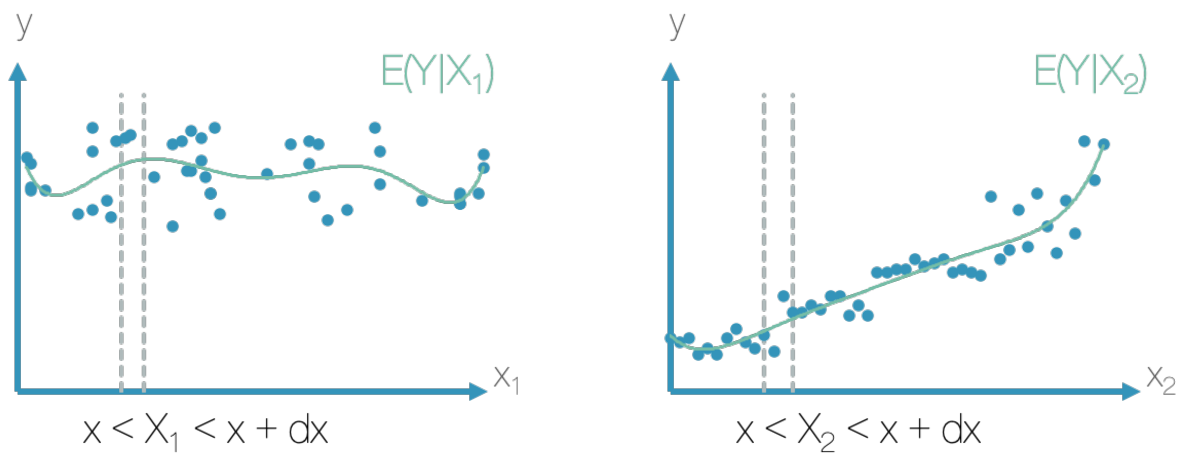

Figure 5.2: Theory of sensitivity analysis illustrates that the influence of X_2 on y in the right image is much more substantial than the influence of X_1 on y in the left image.

measurements.

Theory of sensitivity analysis
A sensitivity analysis is based upon changing values and measuring the effect of that change. This section explains the basis of a sensitivity analysis. In figure 5.2 the values of X_1 and X_2 are plotted versus y. The regression line in green shows the conditional expectation of Y given X_1 or X_2. The increasing trend in the right figure shows that X_2 is much more influential than x_1. Calculating the variation of the conditional expectation can show that influence. The variation of the conditional expectations of the range of y is substantial in the right figure. Whereas in the left figure, the conditional expectation of y lies approximately in the middle. A measure of the sensitivity is to calculate the variance of the conditional expectation over the total variance of y, also shown in equation 5.6 with n parameters of X (Sobol, 2001), (Zhang et al., 2015).

$$\frac{\mathrm{var}[E(Y|X_n = X_n)]}{\mathrm{var(Y)}} \tag{5.6}$$

In theory, any numerical computing model is a mapping of input parameters on output responses. In figure 5.2 the computing model f(x) computes the output response y. Mathematically, any function can be written as a scalar f_0 plus a summing up of functions that evaluated each parameter X_n (the second term of equation 5.7) and a function that evaluates the interactions of two parameters (the third term of equation 5.7 with n' representing any other parameter X than X_n), a function that evaluates the interactions of three parameters, and so on until a function that includes the interaction of all parameters (the last term with X_{N_p} is the last parameter).

$$y = f(x) = f_0 + \sum_{n=1}^{N_p} f_n(x_n) + \sum_{1 \le n \le n' \le N_p} f_{n,n'}(x_n, x_{n'}) + ... + f_{1,2,...,N_p}(x_1, ..., x_{N_p}) \tag{5.7}$$

In that manner and with the assumption of orthogonality of these functions, the variance of y consists of different variances (equation 5.8). This is described by the effect of each parameter (equation 5.9) and the variance due to their interactions (equation 5.10).

$$\mathrm{var(Y)} = \sum_{n=1}^{N_p} D_n + \sum_{1 \le n \le n' \le N_p} D_{n,n'} + ... + D_{1,2,...,N_p} \tag{5.8}$$

$$D_n = \mathrm{var}[E(Y|X_n)] \tag{5.9}$$

$$D_{n,n'} = \mathrm{var}[E(Y|X_n, X_{n'})] - D_n - D_{n'} \tag{5.10}$$

The variance due to each parameter can be approached by S_n (equation 5.11). Also, there are variances due to the interaction between any two parameters over the total variance. If $D_{n,n'}$ is zero, it means that there is very little interaction between the two parameters. This approach can go to higher-order. In this sensitivity analysis, the interaction of all ten parameters is evaluated with Sobols' total effect index (equation 5.5).

$$S_n = \frac{D_n}{\mathrm{var}(Y)}, S_{n,n'} = \frac{D_{n,n'}}{\mathrm{var}(Y)}, ..., S_{1,2,..,N_p} = \frac{D_{1,2,..,N_p}}{\mathrm{var}(Y)} \quad (5.11)$$

5.4.3. Defining low-influence parameter values for the model with GLUE

The previous method explained how a sensitivity analysis can indicate the parameters that have the most significant impact on the output of the model. These parameters are referred to as key-parameter. The key-parameters will need careful in-field measurements to obtain an accurate result. However, the non-key parameters do not require in-field measurements but do need careful approximations to define its default value.

In this section, a method derived from the Generalised Likelihood Uncertainty Estimation (GLUE), defines the distributions and subsequently, the default values for low-influence parameters. The analysis calibrates and validates the parameters.

Aim of the analysis

The objective is to define default values for low influential parameters. The results will reduce the necessary in-field measurements to use the model, described in section 5.3, for a specific tank in a specific location. Also, the use of the model will not depend on a high amount of factors and therefore, becomes more straightforward, easy and fast to implement and use for policymakers, regulators or tank owners.

Theory of GLUE

The method of GLUE generates parameters ranges for the model using Monte Carlo simulation and practices the concept of equifinality. This concept, created by Beven and Binley (1992), accepts the same results for different parameter sets because the set will give a similar response to a certain likelihood. GLUE requires a high amount of simulations with selected random values of parameter sets and focuses on the sets instead of the individual parameter. The method rejects the concept of an optimum value of parameters, which are often generated by other common optimisation methods. The advantage of the GLUE method is that it does not require prior knowledge of individual parameters and therefore, can be sampled uniformly across the specified ranges.

Beven and Binley (1992) describe different steps for GLUE, which include sampling a high amount of parameter sets via uniform sampling. After that, the model runs each parameter set for a great number of times and compares the output to the record of observed values. The performance of the values is assessed with a likely measure, in this case, the Nash and Sutcliffe efficiency (Neto et al., 2013). The evaluation also includes rejecting parameter sets that perform insufficiently. The efficiency evaluates the likelihood of the simulation. Important note from the analysis is that, due to a lack of data, in this study, the modelled values are not compared directly to observed values, but compared to the recorded values of different other studies. Therefore, the uncertainty of the analysis is larger, which explains also why the analysis calculates the ranges and values only for low-influential parameters and not for high-influential parameters.

Monte Carlo algorithm

Monte Carlo (MC) methods are a class of numerical algorithms that draw random samples from a probability distribution to solve deterministic problems. The algorithm runs with a high amount of iterations where it uses the law of large numbers (LLN) to obtain results. Within probability theory, the LLN describes the result after conducting an action or experiments for a large number of times, the average of the outcome is close to the expected or actual value. The result becomes closer to the expected values with more iterations (Artstein and Vitale, 1975).

Calibration

The results of the sensitivity analysis indicate key-parameters. Any calculation or determination of emptying frequencies will depend on the values of the key parameters. The non-key-parameters of the sludge accumulation will have a default value. Two calibration phases determine the distribution and values of these non-key parameters:

1. Phase one calculates the distribution of the non-key parameter values for all possible combinations

Table 5.3: Sludge accumulation data reprinted from Nnaji and Agunwamba (2012)

Time (years)	Volume of Sludge accumulated (m^3/capita)	Period of monitoring (year)	Number of septic tank	Source
0.5	0.046	5	28	(Gray, 1995)
1	0.047	3	727	(Bounds, 1995)
2.8	0.174	8	486	(Bound, 1990)
4.8	0.29	8	486	(Bound, 1990)
5	0.325	5	28	(Gray, 1995)
8	0.378	8	486	(Bound, 1990)

of a high, medium or low value of key-parameters. There are 3^n possibilities for n key parameters. For each combination, the model draws one million random parameter sets. The sets are drawn with some parameter specific boundary conditions, indicated in table 5.1 and 5.2. The boundary conditions are derived from the sources in the tables. After the random sampling, the model validates the set, explained in the next section;

2. Phase two consists of the same exercise as in phase one, but instead of drawing samples from a uniform distribution, the samples are drawn from the calculated distributions of phase one. This generates distributions of the parameters with a smaller uncertainty. The default values for the model represent 50-percentile values of these distributions.

Table 5.1 and table 5.2 show the parameter ranges used in the analysis. The solid specific characteristics values are based upon a literature review, indicated in the table. The tank specific characteristics are derived from commercially available tanks and a literature review. The surface area and height of the tank lead to a minimum and maximum volume. These values are verified with a data source from Englund and Strande (2019). The range of β, equation 5.3, is estimated using the sludge accumulation rate shown in previous studies (Maunoir et al., 2007), (Kinsley et al., 2005), (Gray, 1995). The effluent height is 0.3 m below the height of the tank (NYSDH, 2010).

$$N = 1 - \frac{\sum_{n}^{i=1} (V_{l,i} - V_{Vm,i})^2}{\sum_{n}^{i=1} (V_{l,i} - \overline{V}_{l,i})^2} \tag{5.12}$$

Validation
The data from the volume of sludge accumulation from the literature, shown in figure 5.3, validate the outcomes of the calibration process in each phase. Equation 5.12 evaluates the fitness of the model where V_l is the accumulated volume published in the literature and $\overline{V}_l$ its average. V_m is the simulated volume of the sludge. A N value close to 1 means a well fit with the accumulation models demonstrated (Neto et al., 2013).

5.4.4. Estimating the required emptying frequency

The model will calculate the recommended emptying frequency by using the key parameters as variables. The non-key parameters values will have default values. An important assumption here is the operational judgement: *what is a safe level or state at which a tank needs to be emptied?*. Table A.1 in Appendix A.2 shows an overview of the published guidelines that are used by governments. Overall, governments provide two types of guidelines on when to empty the tank: 1) the volume of sludge has filled up to a certain proportion of the tank (1/4 - 1/2 of total volume); and 2) the sludge reaches a level relative to the effluent line or bottom of the tank (400 mm from the bottom, sludge level of 200-300 mm). Literature shows desludging volumes at 30-50% of the tank (Kinsley et al., 2005), (Gray, 1995), (Weibel et al., 1955). In order to get a as safe as possible desludging period, the model uses the minimum desludging levels for a small (V = 2 m^3), medium (V = 10 m^3) and large tank (V = 25 m^3) (derived from table 5.2).

5.4.5. Development of a user tool

This section elaborates on the design process of a tool that translates easily the results of the model to specific recommendations for multiple users. The methodology used for this section is derived from Sage and Armstrong (2000) and the basic steps are shown in figure 5.3.

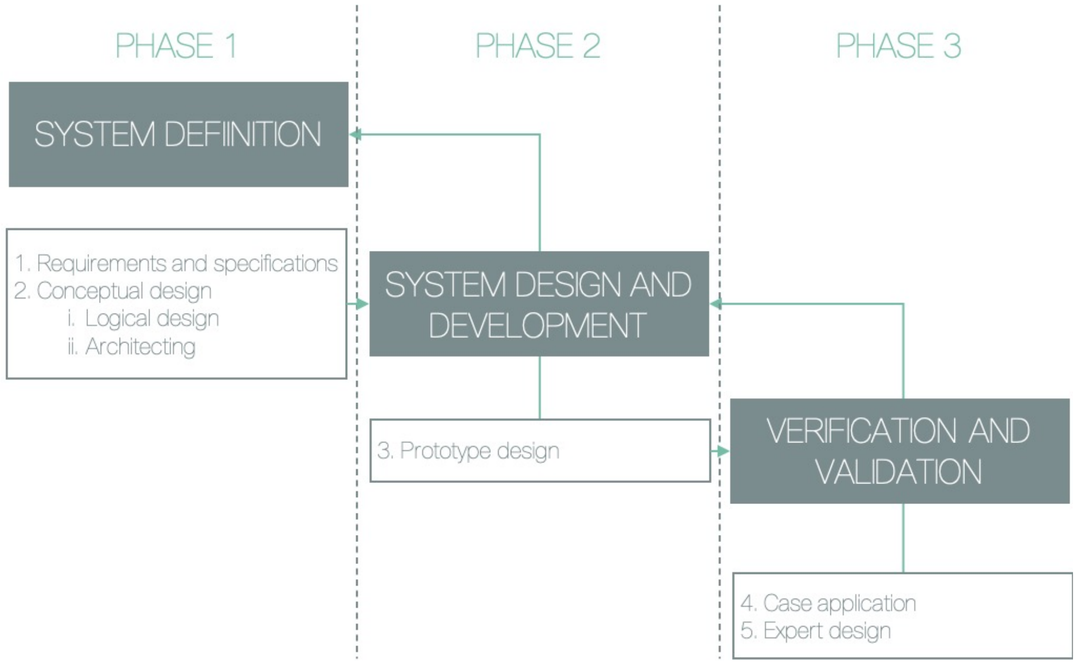

Figure 5.3: Steps of the system design method (Sage and Armstrong Jr, 2000)

Prior to the start of the design process, it is essential to carefully set the needs and objectives of the tool. These requirements form the basis of the design and structure of the tool. After designing the tool, the last phase consists of validating and verifying whether the tool does what it has to do, is usable and is valid.

System definition
In order to define clearly the needs and objectives of the tool, it is important to assess who are the users that would have interest in the tool. Different users have different needs and careful considerations of those needs are important. The identified needs enable to list constraints and requirements that shape the basis of the tool.

System design and development
The first step of the design phase is to create high-level architectural specifications, which defines the functional requirements of the tool. Subsequently, the design of the tool is considered. The tool will be designed in Virtual Basic for Applications (VBA), a programming language developed by Microsoft Office and part of Excel. This ensures that the tool is accessible for a high number of users.

Verification and validation
The verification and validation of the tool are done by peers. The tool is tested to see whether it satisfies the requirements and specifications. Testing the usability of the tool by potential users is essential before the tool will be launched.

5.4.6. Test methods for in-field measurements of key-parameters

In order to use the model, key parameters will have to be tested in the field. A desk review will examine different test methods and will identify the main attributes that should be considered allocating a specific test.

5.5. Results

5.5.1. Sensitivity analysis

Main results: identification of the water content and specific gravity as key parameters. The water content and specific gravity show the most substantial influence on the output of the model and are identified as key-parameters. The OAT sensitivity analysis and Sobol' first and total order analyses show the high impact of the water content. The specific gravity shows, especially in the OAT sensitivity analysis, the most significant negative correlation with the output of the model. The high effects of these parameters are closely linked to their location in the sludge accumulation formula (equation 5.4): the main components of the denominator. The specific gravity and water content of settle solids determine the density of sludge, which converts the mass of settleable solids in the tank into the volume and is, therefore, highly influential for the volume of sludge accumulating in the tank.

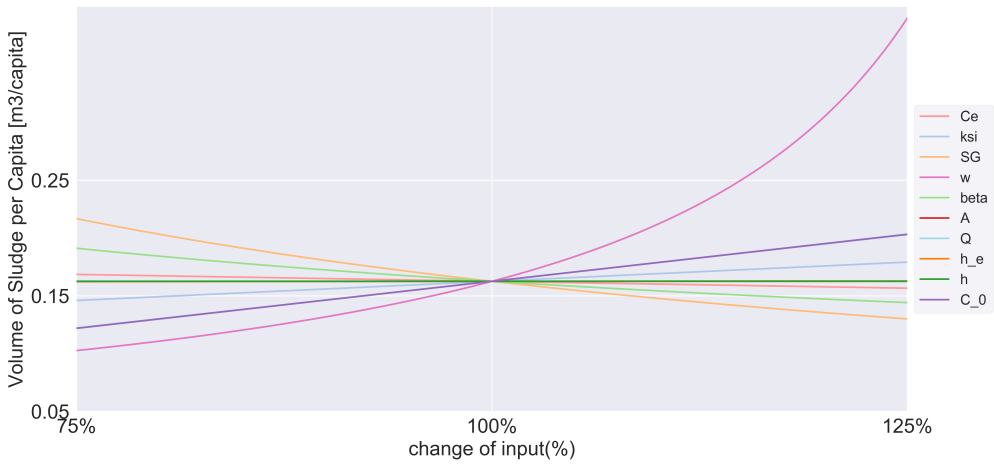

Figure 5.4: Local sensitivity analysis shows the high influence of the water content and effluent concentration

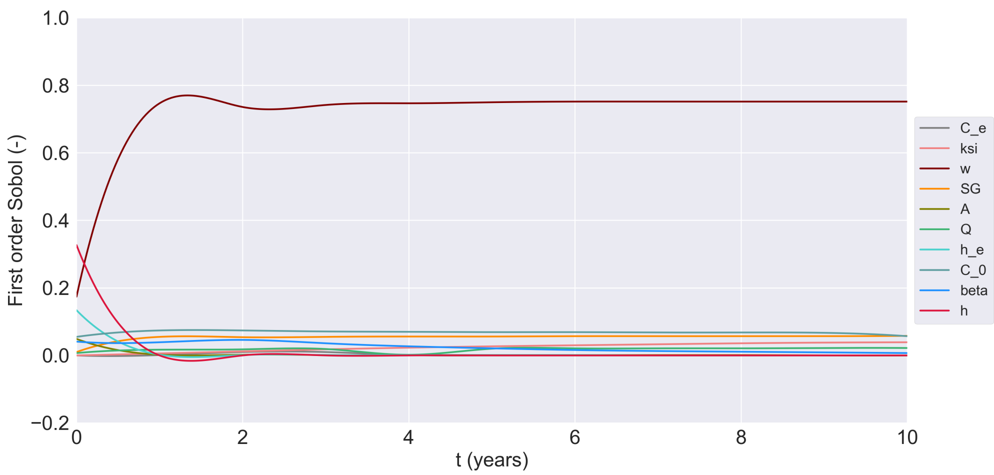

Figure 5.5: Sensitivity analysis shows the high first order effects of the water content

Details from OAT sensitivity analysis

Following the procedures explained in section 5.4.2, figure 5.4 presents the sensitivity of the ten parameters to the volume of sludge accumulation in the tank with OAT sensitivity analysis. This analyses was performed

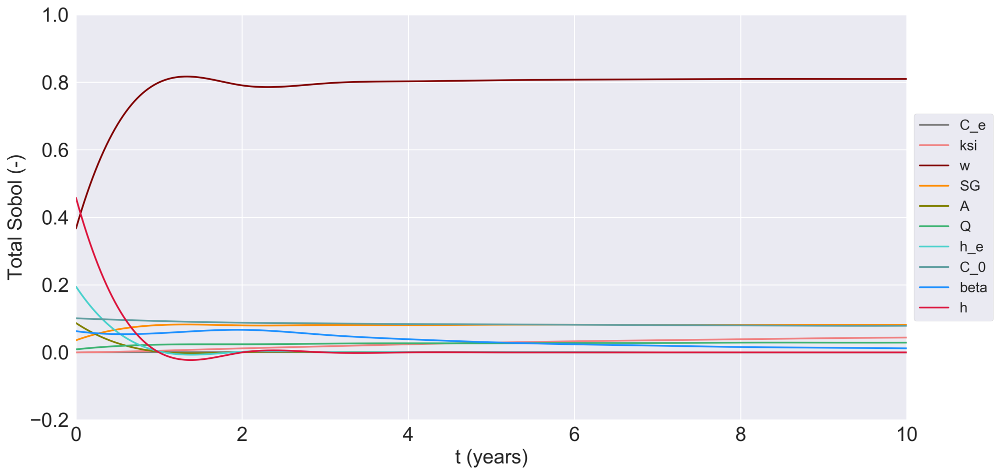

Figure 5.6: Sensitivity analysis shows the high total effects of the water content

using initial data from literature (tables 5.1 and 5.2).

Figure 5.4 shows clearly the high correlation of the water content of the sludge (w) and the high negative correlation of the specific gravity of the sludge (SG). The height of the tank and the effluent height show an almost identical pattern which explains why the bright green line overlaps the orange green line. The graph line of raw sewage flow rate (Q), the height of the tank (h), the effluent height of the tank (h_e), effluent concentration (C_e) and the value of β show a relatively flat line. This trend indicates that these parameters have little influence on the volume of sludge accumulating in the tank. The mildly growing trend of the influent concentration line (C_0) illustrates the moderate impact of C_0 on the output of the model.

Details from Sobol' global sensitivity analyses
Figure 5.5 and 5.6 present the first order and total effects for the Sobol' method. The y-axis shows the magnitude of effects. The x-axis represents the time in years. Since the response varies over time, all sensitivities will vary over time and therefore, the influence of the parameters will alter over time. This is also expected due to the non-linear character of the model.

The water content is an important parameter in both the single effect as the total effect (dark red line). Also, it is visible that the importance of water content increases over time until 2 years, after which, the importance remains the same. The influent concentration (blue line) shows relatively high importance in first-order and total effects. Also, it is visible, that the importance of the specific gravity (orange line), increases slightly in the first years. The importance of the height of the tank (red), the effluent height of the tank (turquoise) and area of the tank (green line) decrease in the first year and shows after that very little effect.

5.5.2. Parameter values for non-key parameters

In the previous section, the water content and the specific gravity are identified as key parameters. This section shows the results of the iterations of the Monte Carlo simulations (after the calibration and validation step). For each Monte Carlo simulation, a combination of a low, medium or high value of the water content of settleable solids and the specific gravity of sludge is used. This means that there were in total per iteration nine Monte Carlo simulations. Table 5.4 shows each combination of water content and the specific gravity of each simulation.

Distribution from first iteration
Figure 5.7 shows the histograms that resulted from the first iteration of the Monte Carlo simulations. These histograms visualise the calculated distributions for each parameter starting from a uniform distribution. Tables 5.5 and 5.6 show the mean values and standards deviations from the results. The distributions correspond well to the results expected from the literature review. Overall, the densities of all tails are relatively

Table 5.4: Nine calibrations using combinations of a low, medium and high water content and specific gravity

Calibration #	1	2	3	4	5	6	7	8	9
Water content (-)	0.8	0.85	0.9	0.8	0.85	0.9	0.8	0.85	0.9
Specific gravity (-)	1.1	1.1	1.1	1.25	1.25	1.25	1.5	1.5	1.5

Table 5.5: Mean values of the Monte Carlos simulations

	SG = 1.1 (-)			*SG = 1.25 (-)*			*SG = 1.5 (-)*		
	w = 0.8 (-)	*w = 0.85 (-)*	*w = 0.9 (-)*	*w = 0.8 (-)*	*w = 0.85 (-)*	w = *0.9 (-)*	*w=0.8 (-)*	*w = 0.85 (-)*	*w = 0.9 (-)*
C_e (kg/m^3)	0.177	0.152	0.125	0.179	0.168	0.138	0.206	0.173	0.145
χ (-)	0.459	0.439	0.418	0.473	0.449	0.415	0.462	0.460	0.441
β (-)	-4.05	-4.45	-4.48	-3.95	-4.27	-4.86	-3.94	-4.13	-4.61
A (m^2)	12.9	12.42	11.26	13.24	12.55	11.55	13.18	13.32	12.41
Q (m^3/day)	177	168	155	172	171	158	184	182	167
h (m)	2.92	2.94	2.60	3.00	2.88	2.80	2.97	2.92	2.83
C_0 (kg/m^3)	0.313	0.269	0.218	0.327	0.294	0.245	0.383	0.308	0.254

Table 5.6: Standard deviations for each Monte Carlo simulation

	SG = 1.1 (-)			*SG = 1.25 (-)*			*SG = 1.5 (-)*		
	w = 0.8 (-)	*w = 0.85 (-)*	*w = 0.9 (-)*	*w = 0.8 (-)*	*w = 0.85 (-)*	w = *0.9 (-)*	*w = 0.8 (-)*	*w = 0.85 (-)*	*w = 0.9 (-)*
C_e (kg/m^3)	0.193	0.174	0.158	0.184	0.185	0.166	0.211	0.191	0.169
χ (-)	0.235	0.232	0.235	0.241	0.246	0.236	0.238	0.238	0.245
β (-)	2.54	2.59	2.61	2.51	2.55	2.65	2.63	2.57	2.62
A (m^2)	10.6	10.7	10.2	11.0	10.9	10,1	10.8	10.7	10.8
Q (m^3/s)	109	108	106	104	110	105	108	109	111
h (m)	2.18	2.27	2.23	2.30	2.25	2.29	2.30	2.21	2.22
C_0 (kg/m^3)	0.361	0.316	0.274	0.337	0.328	0.332	0.394	0.354	0.295

high. For the tank specific parameters (discharge rate, height and area) this was unexpected, compared to the literature review. The underneath section elaborates further on these results in more detail.

Effluent concentration of settleable solids
Most effluent concentrations are approximately 0.1 kg/m^3 (top left plot in figure 5.7). There is a relatively high distribution between 0.2 and 0.4 kg/m^2. After that, the distribution flattens out. These numbers correlate to the range found in the literature for the effluent concentration, which was 0.002 - 0.149 kg/m^3. The effluent concentration has a mean value between 0.125 and 0.206 kg/m^3 (table 5.5). The mean concentration decreases for higher values of the water content and increases for higher values of the specific gravity. The standard deviation shows the exact opposite trend: higher values of the water content appear to lead to a lower standard deviation, higher values for the specific gravity show higher standard deviations

Fraction of solids that are non-biodegradable (χ)
The median of the fraction of non-biodegradable solids is 0.42 (-) which is also clearly visible in the graph (top right plot of figure 5.7). The density is in general large over the whole range between 0-1. This can indicate the large spectrum of content entering into the tank (section 2.2). For some users, only faecal matter enters into the tank (where the substances and masses differ from user to user). Other users throw a substantial amount of waste inside their tank. Also, the materials used for anal cleaning differ greatly among countries and cultures. The mean value of the fraction of solids ranges between 0.415 and 0.473 (-) (table 5.5). The standard deviation of the non-biodegradable parts has little fluctuations.

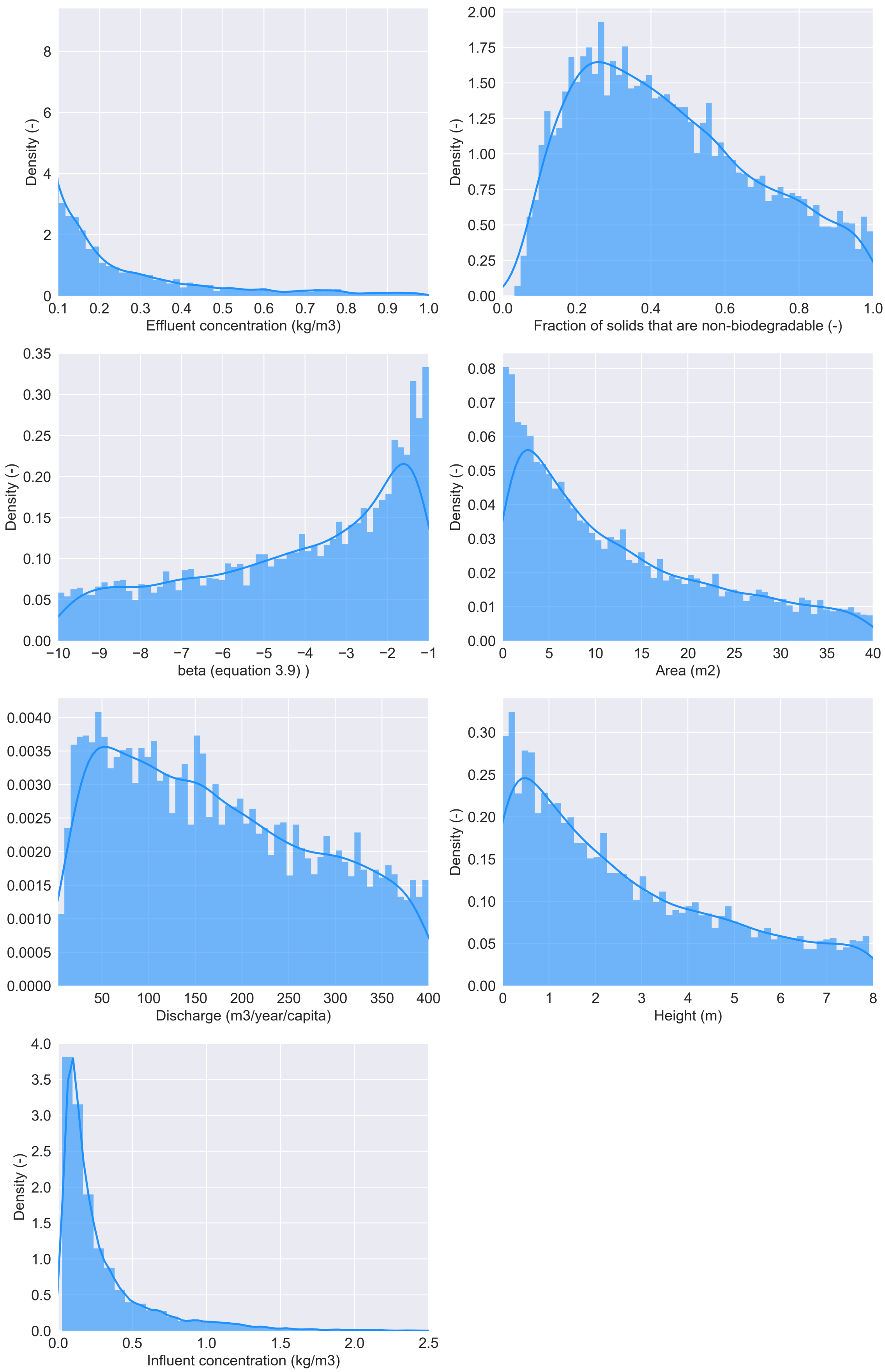

Figure 5.7: Distribution of the parameters from a uniform sampling and Monte Carlo analysis

β - equation 3.9
β shows the highest density at approximately -1. The median of the density is at -3.3. β shows a considerable distribution from -3 until -10 (second plot in the left row of figure 5.7). The mean values of β show an increasing trend for increasing values of the water content and a slightly decreasing trend for higher values of the specific gravity (table 5.5). The standard deviations fluctuate little (table 5.6).

Area of the tank
In this graph, it seems like the area of the tank can range from 0-40m^2 (second plot in the right row of figure 5.7). However, in the commercially available tanks found during a desk review, the areas of the tank were never bigger than 25 m^2 (table 5.2). From the graph, it also follows that most tanks have an area smaller than 10 m^2. The density is higher for smaller tanks. The mean area of the tank is in a range of 11.26 - 13.32 m^2 (table 5.5). The relatively high mean values of the area (compared to the commercially available tanks) are because of the presence of a low density of exceptional large tanks. There is a trend visible where higher values of the specific gravity show higher values of the area.

Discharge rate
The discharge rate has a broad range (third plot on the left in figure 5.7). This might indicate that users utilise their tanks for different purposes. Where some users only use the tank for faecal matter, other users connect their greywater on the tank as well. The peak of the density is around 50 (m^3/year/person). This peak is in line with the values found in the literature.

The mean value of the discharge rate (table 5.5) is high compared to the values found in the literature (table 5.1). This discrepancy is because of the small presence of high discharge rates. The table shows higher discharge rates for lower water contents and higher specific gravity values. This trend implicates that high discharge rates are not necessarily caused by a high rate of water approaching the tank, but with a high rate of denser material. The standard deviation of the discharge rate is substantial. This could be an indication that the tank can be connected to different types of water (greywater or blackwater) (section 2.2).

The height of the tank
The most significant distribution of the height of the tank is approximately between 1.5 and 2 m (third plot on the right in figure 5.7). This peak corresponds with commercially available tanks (table 5.2). In the desk review around commercially available tanks, septic tanks were not higher than 3 m. However, the density plots show also relatively large density at tanks higher than 3 m. The mean values for the height of the tank (table 5.5) are quite high compared to commercially available tanks (table 5.2). This trend is because of the long tail of the density plot, which is also visible in the large standard deviations shown in table 5.6.

Influent concentration of settleable solids
The influent concentration of the tank shows a high peak from 0-3 kg/m^3 and a reasonable density from 0.3 - 1 kg/m^3 (bottom plot in figure 5.7). The literature review indicated an influent concentration from 0.084-0.33 (table 5.1). These values are highly comparable. The mean values of the influent concentration are in a range from 0.218 - 0.383 kg/m^3 (table 5.5). Due to the long tail of the density plot (figure 5.7), the standard deviation is significant. This long tail also indicates that the concentration of the settleable solids entering the tank can fluctuate significantly, because of different practices (section 2.2)

Distribution from second iteration
In the previous section, the first iteration made estimations of the distributions of all non-key parameters, starting from a uniform distribution. The following section presents the results from the second iterations, which executed the same steps but instead of sampling from a uniform distribution, it sampled from the estimated distribution.

Again, for each Monte Carlo simulation, a low, medium or high value of the water content of settleable solids and the specific gravity of sludge is used. This means that there were in total per iteration nine Monte Carlo simulations. Table 5.4 shows each combination of water content and the specific gravity of each simulation. Figure 5.8 shows the distributions of the nine Monte Carlo simulations and table 5.7 shows the mean and variance of the second iteration. As expected, the tail is flattened for all graphs. The new distributions are more concentrated around the peaks. Especially, the values for the area and height of the tank, show values

Table 5.7: Default values generated for parameters based on 25 and 50 percentile and mean values of second Monte Carlo simulation

	Values					
	25-ile	*50-ile*	*75-ile*	*mean*	*std*	*units*
C_e	0.03	0.05	0.08	0.05	0.05	*kg/m*^{3}
χ	0.33	0.43	0.56	0.45	0.2	-
β	-1.57	-1.31	-1.13	-1.4	0.4	*(equation 3.9)*
A	1.72	4.64	10.41	7.65	8.2	*m*^{2}
Q	92.47	154.5	235	169	95.55	*m*^{3}*/day*
h	1.05	2.28	4.22	2.8	2.15	*m*
h_e	0.46	1.26	2.63	1.8	1.8	*m*
C_0	0.09	0.14	0.21	0.20	0.15	*kg/m*^{3}

that are more similar to the values found in commercially available tanks compared to the values that resulted from the uniform parameter range.

Table 5.7 shows the 25-percentile, 50-percentile, mean and variance values of the second Monte Carlo analysis. The 25-percentiles give the value below 25 per cent of the values fall. The same counts for the 50 and 75 percentiles, which is why the 25 percentile, 50 percentile and 75 percentile show increasing values. The 50 percentile is also called the median and gives the middle value; 50 per cent falls either above or under that certain value. The calculations of the emptying frequencies use the median values.

Validation of results
Figure 5.9 shows the accumulation of sludge, using the calculated default values and different values for the key parameters. The dark blue line indicates the volumes of literature. The sludge accumulation show a 0.97 Pearson correlation factor with Weibel et al. (1955) and a factor of 0.9 with Bassan et al. (2014). The strong influence of the water content is clearly visible, since the top and the bottom line represents the highest and lowest emptying frequency respectively, which also corresponds to the highest and lowest values of the water content.

Table 5.8: Emptying frequencies in years for a medium size tank and a emptying requirements of 1/4 full tank in years

	SG = 1.1			*SG = 1.25*			*SG = 1.5*		
	w = 0.8	*w = 0.85*	*w= 0.9*	*w = 0.8*	*w = 0.85*	w = *0.9*	*w=0.8*	*w = 0.85*	*w = 0.9*
Amount of users									
3	19	14	9	21.5	16	10	26	19.5	12.5
4	14	10	6	16	11.6	7.5	19.5	14	9
5	11	8	5	12.5	9	5.5	15	11	7
6	9	6	4	10	7.5	4.5	12.5	9	5.5
7	7.5	5	3	8.5	6	3.5	10.5	7.5	4.5
8	6	4.5	2.5	7.5	5	3	9	6.5	4
9	5.5	4	2	6.5	4.5	2.5	8	5.5	3.5
10	5	3	2	5.5	4	2	7	5	3

5.5.3. Defining the emptying frequency of septic tanks

Based on the default parameters values and the specific values for water content and specific gravity, operational predictors of emptying frequency were found and shown in figure 5.10. The figure shows how different

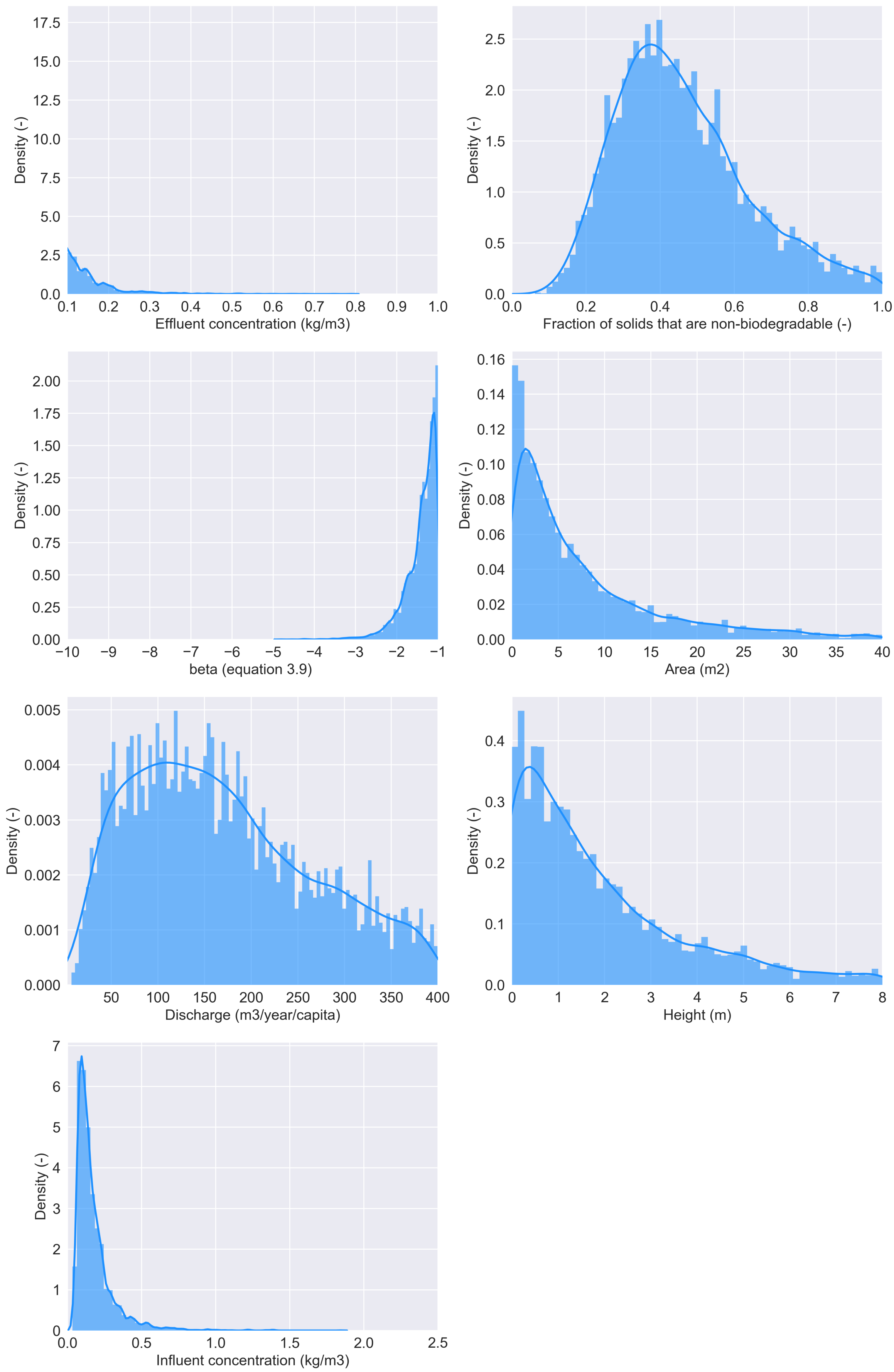

Figure 5.8: Results from the Monte Carlo analysis after sampling from the calculated distributions (2nd iteration)

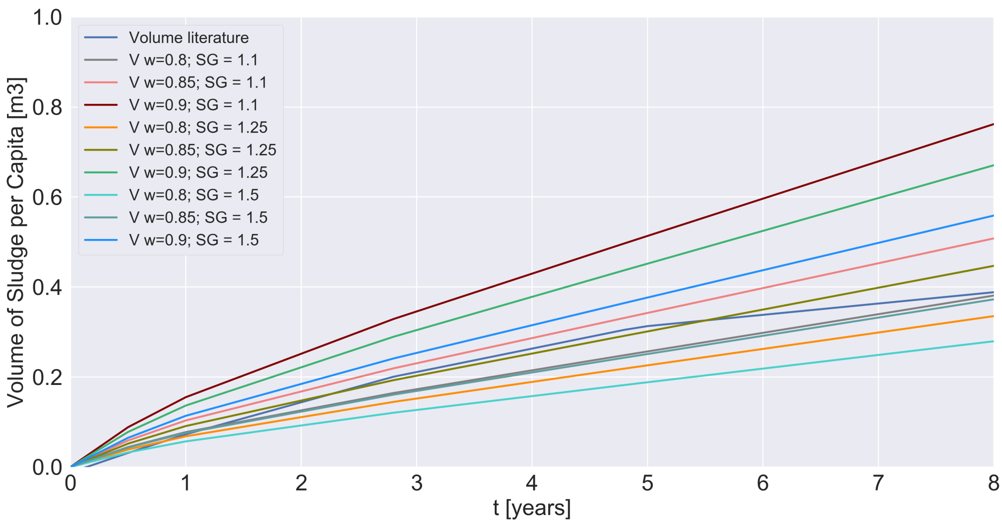

Figure 5.9: Simulation of the default values with different values for the key-parameters

Table 5.9: Emptying frequencies for a medium size tank and a emptying requirements of 400 m of sludge on bottom of the tank

	SG = 1.1			*SG = 1.25*			*SG = 1.5*		
	w = 0.8	*w = 0.85*	*w=0.9*	*w=0.8*	*w = 0.85*	w = *0.9*	*w=0.8*	*w = 0.85*	*w = 0.9*
Amount of users									
3	13.5	10.	6.	15.5	11.5	7.	19.	14.	9.
4	10.	7.	4.5	11.5	8.	5.	14.	10.	6.5
5	7.5	5.5	3.	9.	6.5	4.	11.	8.	5.
6	6.	4.5	2.5	7.	5.	3.	9.	6.5	4.
7	5.	3.5	2.	6.	4.	2.5	7.5	5.	3.
8	4.5	3.	1.5	5.	3.5	2.	6.5	4.5	2.5
9	3.5	2.5	1.5	4.5	3.	1.5	5.5	4.	2.
10	3.	2.	1.	4.	2.5	1.5	5.	3.5	2.

combinations of water content and the specific gravity of sludge change the prediction of the emptying frequency. This is also indicated in table 5.8, table 5.9 and figure 5.9. A higher water content leads to a higher emptying frequency. A higher value of the specific gravity leads to a lower emptying frequency. Reducing the amount of water in sludge can alter the emptying frequencies up to 52%. Changing the content that enters the tank to solids that have a lower specific gravity, can reduce the emptying frequency up to 28%.

Table 5.9 and 5.8 show the predictions of emptying frequencies for different guidelines. Comparing the two tables illustrates the large discrepancies between currently used guidelines. The different safe levels can lead to a difference in recommendations of up to 7 years.

To make the results easy to be implemented by users, figure 5.11 shows how often a tank should be emptied based upon the volume of the tank and the number of users. This graph is specific for a medium amount of water (w=0.85) and a low amount of specific gravity (SG=1.1). The assumption here is that the maximum safe level of sludge inside a septic tank is 25%, after which it should be emptied. The other eight combinations of water content values and specific gravity values that are used are shown in Appendix E.

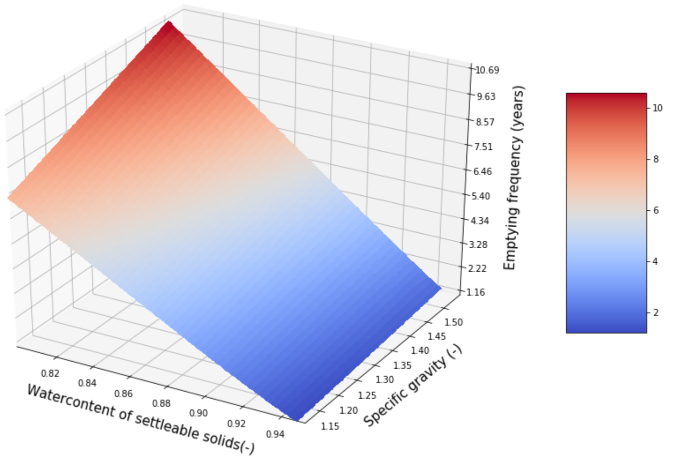

Figure 5.10: 3D figure of the calculated emptying frequency with a emptying level of 0.25% full for a household of five people

5.5.4. User tool

The aim of the user tool is to provide tank users with the recommendation of the model in a simple manner. In order to make the user tool easy to use and to avoid any software thresholds, Excel was chosen to run the tool. The macros of Virtual Basic of Applications (VBA), inside Microsoft Excel, enables a consistent manner of user input, that reduces the chances of errors and misuse. The next section will first present the identified requirements and specifications of the tool.

System definition

Users

- owners or managers of septic tanks;
- regulators;
- policymakers.

Requirements

- **simple**: the tool should be easy to use for anyone who has basic IT-skills;
- **open source**: the chosen software for the design and execution of the tool should be commonly available for users and preferably, no additional software should be required to be installed;
- **flexible**: different combinations and formats of data input should be usable since the availability of data might fluctuate among users;
- **accurate**: the outcome of the results should be precise and assumptions should be kept to a minimum;
- **efficient**: the tool should lead to results for users within a short period of time and the output of the tool should generate an attractive recommendation that is easily adoptable (e.g. using half a years, instead of decimal years

System design and development
Main process
Figure 5.12 illustrates the high-level function structure of the tool. This shows the functionalities for the different users. The start of the assessment is initiated with the pop-up of a self-explanatory user form. The

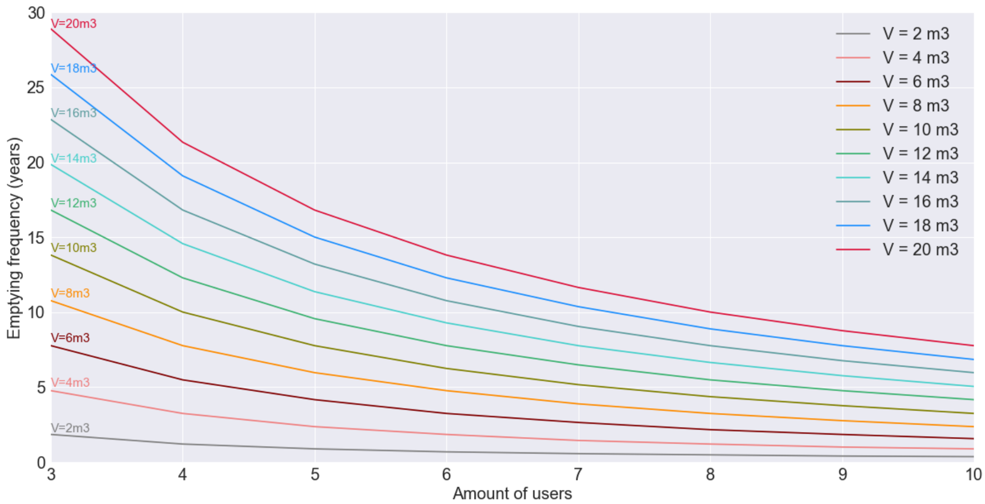

Figure 5.11: Caption

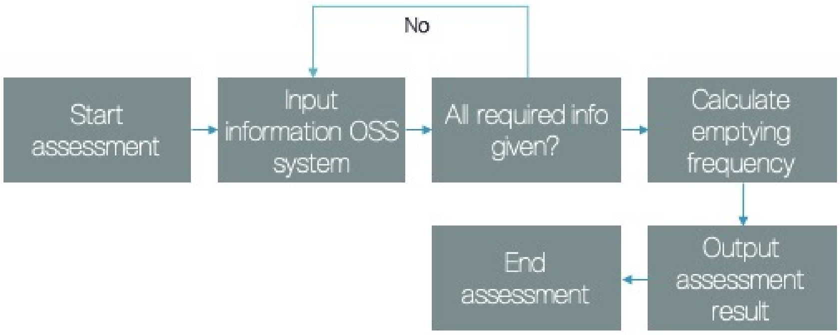

Figure 5.12: Flowchart of the main processes of the tool

users need to fill in information about their system. The key-parameters (the water content and the specific gravity) are obligatory. The input of the volume of the tank and the number of users of the tank are optional decisions that would increase the accuracy of the outcome. Once all relevant data have been entered into the system, the user presses the *calculate* button. The terminal shows the outcome of the recommended emptying frequency.

Sub assessment
The sub assessment searches for the recommended emptying frequency, based on the input that is provided by the users. The user's input determines the data sheets that are looked into. In total, the user tool has 27 worksheets. There is however only one sheet that can be accessed by the user; this is done to avoid any confusion for the user.

Layout
Figure 5.13 shows the layout of the tool. In the front sheet, the user form is shown. In the background, the calculation form is shown. In general, the user does not have to close the user form at any time (and it opens automatically when the file opens).

Verification and validation
The tool has been verified and checked to confirm all functionalities are working correctly. During this phase, certain errors were discovered and adjusted in the development phase. Afterwards, the tool has been tested by five peers. No additional errors were found. Also, the emptying frequency tool meets the requirements

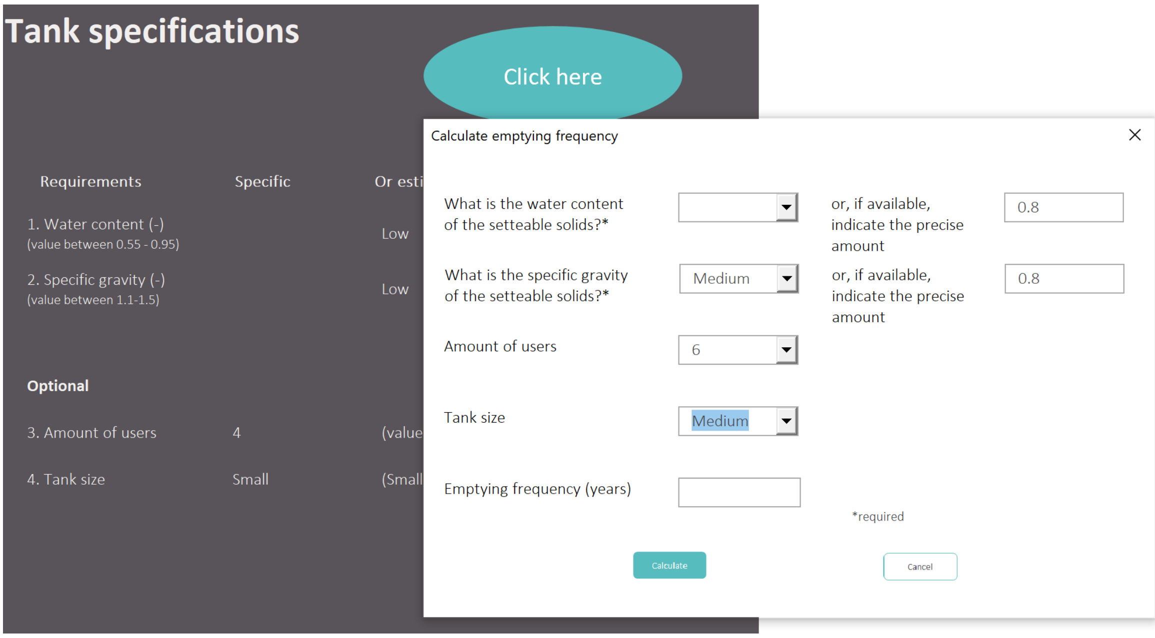

Figure 5.13: Layout of the user tool

stated in the previous section. However, before launching the tool needs to be tested among potential users of the tool. This step is of paramount importance.

5.5.5. Methods to measure key-parameter values

The use of these tables and tool require measurements of water content and the specific gravity of the sludge. Different measurements methods of water content are compared. The descriptions of these methods are in Appendix F. The results of this desk review show that there are different options to test the water content and specific gravity of sludge. However, to make the test feasible for large-scale technical inspections, the test should fulfil the underneath requirements:

- small amount of time required per test;
- limited necessary technical expertise;
- minimal costs/test; and
- limited necessary equipment (e.g. no power connection).

From the perspective of the desk review, centrifugal tests show the most potential to be a useful measurement tool. As also mentioned in Appendix F, there is limited research on the different characteristics of sludge within a sludge layer. Since the highest density of solids, will be at the bottom, determining the water content and specific gravity at the bottom of the septic tank will lead to the most conservative emptying frequency.

5.6. Discussion

The sensitivity analysis hypothesises that two characteristics (the water content and specific gravity) of the solids inside a septic tank serve as dynamical indicators of sludge accumulation. Estimating the other eight identified characteristics of sludge accumulation with a method from GLUE leads to an approximation of the accumulation of sludge in septic tanks that shows high similarities with other empirical studies. These results provide first, preliminary evidence for the usability of a model to calculate the fill rate in septic tanks which can be used to indicate emptying frequencies for OSS systems.

The modelling questions, as specified in Appendix E, was as follows: *What is the effect of tank characteristics and user's practices on the emptying frequency of septic tanks given that the accumulation of sludge follows a mass balance and the values of the parameters are constant in time*? Based on the results presented in this section and the other figures in Appendix E, the following answers can be given:

- **tank size**: a bigger tank leads to a smaller emptying frequency. However, the impact that a larger tank has on the emptying is larger for a small number of users than for a large number of users.
- **user practices**: the water content has a very large implication on the emptying frequency of the tank. There is a big chance that decreasing the amount of water that is connected to a septic tank, will lead to a smaller emptying frequency.
- **Safe level to empty a tank** it is of paramount importance for this research field to achieve a consensus regarding the safe level of sludge. The difference hereof leads to substantial differences in the recommendations.

The fact that the local sensitivity analysis is done with a factor of 75% to 125% is in contrast with the calculated distributions resulting from the GLUE method. The used factor range may have been too small to results in significant differences for some characteristics, such as the discharge rate. Taking a larger factor could have lead to different key-parameters.

Besides the small range which may have caused this study to underpower the discharge rate, there is another notable limitation to this study. The available studies of different parameters that describe the value of β was limited. To acquire a first estimate of the possible range where the value of β lies in, that value is estimated using the sludge accumulation rate shown in previous studies (Maunoir et al., 2007), (Kinsley et al., 2005), (Gray, 1995). Future studies should research the underlying characteristics of β to 1) assess the importance of these characteristics and determine whether these characteristics would need in-field measurements in order to receive an accurate sludge accumulation rate; 2) to identify boundary conditions of the underlying characteristics so that a full GLUE procedure can be applied to all of the elements of β.

Moreover, the validation of every sampled parameter set is assessed with a limited and rather old data set. Unfortunately, I have not been able to acquire the full data set to analyse the basis of this set. Due to the limited alternatives, I had to use the data published by Nnaji and Agunwamba (2012) and was, therefore, not able to study the locations, conditions or measurements procedures of these data. Including this information, could have provided more insight into the meaning of the validation scores.

In conclusion, the current work is a first step toward quantifying the fill rate for OSS systems in a dynamic way. Although preliminary, the current results offer an exciting prospect for further exploration of dynamical models to estimate emptying frequencies. Eventually, the model may help in generating practical guidelines for policy-makers or users of septic tanks and provide means to explore new opportunities for creating safe sanitation.

6
General discussion

This thesis contains three analyses relevant for the measuring of safe emptying frequencies of septic tanks using a numerical sludge accumulation model with the aim of mitigating hazardous events. The current chapter will briefly summarise the key findings and elaborate on the methodological considerations and implications of the research findings for society and further research.

6.1. Main findings

This thesis aims to contribute to reducing the gap between the theory and science with respect to sludge accumulation in OSS systems and the way the status of OSS systems is often assessed in practice. With the research presented in this thesis, I intended to develop a dynamical approach to viewing and assessing the status of OSS systems by combining sludge accumulation theory and simple in-field observations and measurements. The main research question was: *To what extent is it possible to develop easy and valuable guidelines on the safe emptying frequency of septic tanks from a numerical model that can mitigate hazardous events?* This question was split into a number of sub-questions which will ultimately lead to an answer to the central question of this thesis.

1. *What is the impact of a recommended emptying frequency on the hazardous events in respect of safe OSS tanks?* [1]

Recommended emptying frequency can mitigate the causes of three high-risk hazardous events: groundwater pollution, local watercourse pollution and surface flooding. Providing a recommended emptying frequency may offer a way forward in personalising recommendations towards the prediction and management of particular OSS systems. Clear guidelines on the amount of time that lapses between two emptying events of OSS system can encourage responsible behaviour of users to empty their OSS system in time before noticeable problems develop. Also, recommended emptying frequencies can make it easier for policymakers to 1) assess whether a specific OSS system is safe or not; and 2) to monitor the status of OSS systems on a national or even a global scale and, if necessary, help governments in establishing national or local guidelines to improve the safety of OSS systems. With the above in mind, a recommended emptying frequency can mitigate the risks of specific hazardous events from occurring and hence improve the safety of OSS systems.

2. *In what way can we develop a numerical model to predict the sludge accumulation in septic tanks?*

This thesis provides evidence for the feasibility of constructing a numerical model as a measure to simulate sludge accumulation in septic tanks. The modelled simulation of sludge showed highly similar results to two different empirical studies that measured the accumulation of sludge. Using a simple mass balance that evaluates the faecal matter entering into the tank, the mass that leaves the tank, the mass that is decomposed anaerobically and the growth of bacteria lead to a valid prediction of the sludge accumulation in septic tanks. Because the model uses a combination of default values and values resulting from in-field measurements, the model is able to make accurate estimations using as little in-field measurements as possible.

[1] All of this, on the assumption that users of OSS systems would follow-up on the recommendations

3. *How can we test the status of an OSS tank based on the numerical model?*

A combination of in-field measurements and defaults values can estimate the necessary sludge accumulations in septic tanks based on a numerical model. These results can suggest a required emptying frequency for different tank sizes and different number of users thereof. Adding the results of household surveys or censuses, which include information on the *actual* last time a tank has been emptied, will have significant additional value to determine whether the sludge volume inside the septic tank is at a safe level or not. The (un)safe status of an OSS tank can be derived on the basis of the *actual* last time a tank has been emptied and the *required* emptying frequencies.

In conclusion, a numerical model on the accumulation of sludge offers opportunities to take the assessment of OSS systems to higher levels and mitigate hazardous events. The results of the model may provide guidance to the users of septic tanks. In addition, the model supports policymakers to monitor and assess the safety of OSS systems, which will help to target intensive improvements and preventative/supportive solutions to regions or communities which will likely benefit most from these.

6.2. Methodological considerations

To facilitate future research, the following paragraph will clarify several methodological considerations concerning the use of a numerical model in combination with a non-site specific risk assessment to mitigate hazardous events, with practical examples taken from the work presented in this thesis.

Constraints of the risk assessment

The identification of hazardous events has for the most part been executed on the basis of a literature review, which allows for subjectivity and ‘luck‘ to list certain hazards/hazardous events/causes of hazardous events instead of others. The drawback is that these hazardous events are not empirically identified as frequent hazards. When applying the non-site specific risk assessment, a number of challenges were encountered. This section describes the constraints of identifying non-site specific hazardous events that I came across and lessons I learned during the work contributing to this thesis. To solve, circumvent or become aware of these issues in future studies, I recommend the following six crucial steps in thinking before designing a new non-site specific risk assessment. The bottom line is that a non-site specific risk assessment should never be *blindly* analysed by a single individual that does not have a profound understanding of the functionalities, usage or site-specific conditions of the OSS systems of interests. If the researchers or policymakers do not think about the conceptual basis of the functionalities of the OSS systems, in a specific context, misunderstandings and misuse of the risk assessment may easily arise.

Recommended step-by-step approach when applying a non-site specific risk assessment for OSS systems. All steps should be executed with validations of expert judgments

1. Define OSS systems and their components (influent or effluent lines, permeable layers);
2. Define a safe status which will not lead to health risks;
3. Define a time scale at which the unsafe status should be restored;
4. Define system scenarios (e.g. user behaviours and site conditions);
5. Define hazards, hazardous events and causes of hazardous events for each scenario;
6. Identify the magnitude of the risks.

Subjectivity and ‘luck’. Even with the underlying assumption that an extensive literature study has been done and that the researcher has experiences in the field, a risk assessment, which is based on the judgment of only one expert can never be regarded as an adequate risk assessment. To provide an example, in the structured expert elicitation in chapter 4.3, I found contrasting answers on the different risks allocated to different hazardous events. This observation may be explained by the experts’ subjectivity concerning hazardous events due to their respective experiences with hazardous events and interpretations of the questions. Identifying hazardous events during several group discussions with various experts from different backgrounds and nationalities might be useful in getting to a listing of hazardous events which has a sufficient degree of objectivity and completeness.

System scenarios. Sanitation risks are, in their essence, always related to a specific site or location depending on their local circumstances. The goal of creating a *non*-site-specific risk assessment was to create a global overview of the main risks that contribute to unsafe sanitation so that global measures focus on the most significant health risks. This approach leads to a certain degree of generalisation, in the sense that the impact of two identical hazardous events, taking place at two different locations (with different circumstances) can be totally different. The discrepancies between a hazardous event occurring to an OSS system close to a drinking well and a similar event taking place to an OSS system in the middle of a high-income city, are too significant and can not be named together. For that reason, I would recommend creating a limited amount of scenarios, which include the most crucial site-specific characteristics, that cause the differences in terms of consequences between two or more hazardous events. Subsequently, a similar risk assessment could be applied to equal scenarios taking place at different locations (with equal circumstances). After which, an expert judgment could assess the risks of specific hazardous events for a specific scenario, which eventually creates an interesting overview of the main risks that contribute to unsafe sanitation, which can ensure that global measures are appropriate to control these significant health risks. Finally, it will facilitate the use of solutions or implications from one location and apply this solution to another location within the same scenario.

Identification and performance assessment of experts

Because there was no information available to quantify the risks of hazardous events, the voicing of experts was necessary. By using a *structured* expert judgment, an attempt is made to quantify the uncertainty of the expert opinion. However, this comes at the costs of other uncertainties and drawbacks. With a *structured* expert judgment, the expert' performance is tested with seed questions. However, it appeared to be difficult to generate objective sanitation seed questions. Especially, because the answers to the seed questions are often dependent on the location where the experts have his/her experience. Therefore, implicitly some experts or types of expertise are ruled out of the virtual decision-maker because of the subjectivity of the researcher. It is recommended that the formulation of the seed questions, regular questions and the seed answers, which all have a significant impact on the outcome of the risk assessment, should be considered with a large group of experts to avoid subjectivity and preferences of the researcher. Also, this group should define specific requirements which determine whether an expert meet specific necessary characteristics or qualities that make such a person eligible to give his/her expert opinion. The requirement list should avoid the influence of experts that do not have the relevant experience and/or knowledge that is required for the research.

Real-world phenomena constraining the model

Operationalising the model crucially depends on the ability to validate the distributions of the calculated non-key parameters on a large scale, our ability to measure the key variables in the field and the consensus of a *safe* level or conditions of a septic tank (e.g. when the tank is considered half full or quarter full).

Validating the distribution of non-key parameters. Fluctuating distribution patterns either in underlying conditions or external perturbation may result in distorted patterns in the sludge accumulation. These fluctuations can be periodically (e.g. monthly/seasonal) or on a spatial scale. The method of GLUE validated the calculated accumulation of sludge with limited data sources. It may make more sense to validate the distributions for different time series (e.g. months and years) and locations to investigate these fluctuations for various locations and conditions.

Feasibility of in-field measurement protocol. Using the recommended emptying frequencies requires reliable measurements of the key-parameters: the water content and specific gravity. Due to the large heterogeneity of septic tanks or OSS systems in general, a measurement protocol is typically often not feasible for all septic tanks, let alone for all OSS systems. Based on the desk review, a centrifugal test seemed a good starting point to investigate the possibilities to measure the water content and specific gravity (Appendix F). However, it should be investigated whether periodically fluctuating (e.g. diurnal/weekly/seasonal) patterns may also result in perturbations in the measurements. One should think about the impacts of day-night rhythms, and even structural behavioural influence (e.g. a family always having showers in the morning or evening). In addition, environmental perturbations of a large magnitude may overshadow the underlying characteristics of the systems. Lastly, there is currently a lack of research on the stratification of different sludge characteristics. Further research should be done in this field in order to establish a specific measurement depth of the key-parameters.

Consensus of a safe required emptying level or conditions. When designing a new study to investigate the required emptying frequency based on a model, the conditions or levels at which the tank should be emptied, are important considerations. When modelling the fill rate inside an OSS system, this is the last “simple math” step of the calculations. However, it influences the outcome of the recommended emptying frequency significantly, as is shown in the results of table 5.8 and table 5.9 in chapter 5; using different sludge levels that are regarded as safe altered the recommendations with 7 years. Therefore, a consensus of what is regarded a safe sludge level will lead to more consistency in the recommendations of governments, as they currently seemed to be largely formed on an arbitrary basis (Appendix A).

When is the model (un)suitable to use for other OSS systems
Just like any other quantitative analysis, the usability and reliability of the model largely depend on the underlying equations and available data that determine the model.

Underlying characteristics of OSS system. To reliably transform the model for a septic tank to other OSS systems, it is crucial to analyse in-depth the underlying characteristics of the mass entering into, coming out and being biodegraded. Since the functionalities of a fully lined storage tank are generally similar to a septic tank, the same underlying equations could be used minus the part of mass leaving the tank. This could be a first step of translating the model to another OSS system.

Data availability. The number of sludge accumulation studies for different OSS system will determine mainly the possibilities to calibrate and validate the calculated outcomes. In the case of the fully lined storage tank, it would be interesting to see if the calculated default values from this study for the non-key parameters would lead to accurate fill-up rates that correspond to empirically measured values for fully storage tanks. Because of the significant discrepancies of the incoming and outgoing mass from other OSS systems, one could say that the distributions of the other non-key parameter values should be determined again when applying this method to other OSS systems.

Do users of septic tanks follow up on recommendations?
In the modelling process, the focus was to create *recommendations* regarding the emptying frequency of septic tanks. However, it would be very interesting to research how users of septic tanks would react to the provided recommendations and whether these users will follow-up on these recommendations. I would recommend researching in-depth what the main reasons are why users are not emptying their septic tanks in time and to what extent users are open to follow-up any recommendation on emptying frequencies.

Interdisciplinary research on measuring the accumulation of sludge.
The concept of sanitation is relevant for many disciplines, from economists to anthropologists, from civil engineers to microbiologists or even medical practitioners. This invites for interdisciplinary collaboration. A great deal of knowledge, original ideas and practical support could be gained by working together with sanitation researchers from different fields of expertise. Examples are sanitation for degradation of faecal matter (Finstein and Morris, 1975) for adding economic value (Harris et al., 2011), or as measure to overcome illness (Feachem et al., 1983).

I realise that in sanitation agencies, the collaboration of researchers with different backgrounds takes place on a normal basis. Apparently, this is easier to facilitate than in the academic environment. However, I believe that the problem of sanitation is embedded in our global society and that academic research could gain significant added value when sanitation would be considered in its fullest scope, in collaboration with other disciplines.

Recommendation to advance the use of the model for managers or owners of septic tanks

Goals for users or managers of septic tanks: to obtain valid emptying frequency predictions and to empty their tanks as little as possible.
How

1. investigate the water content and specific gravity of the settleable solids inside your septic tank;
2. if available, give extra information about the number of users of the tank and the tank size;
3. use the emptying frequency *user tool* to find out the emptying frequency for your tank(s);
4. limit the amount of water that enters into the tank;

Recommendation to advance the use of the model for sanitation policy makers or regulators

Goal for policy makers or regulators: to obtain valid emptying frequency recommendations for different households to improve the safety of septic tanks.
How

1. investigate existing data from the regional jurisdiction regarding the water content and the specific gravity;
2. calculate the average household size and tank sizes of your region;
3. advise households to limit the amount of water that enters into the tank;
4. use the simple emptying frequency *user tool* to find out the recommended emptying frequencies for standard households using the above-mentioned data;
5. compare the acquired data from census or household surveys with the recommended emptying frequency calculated from the tool to get an estimate about the safety of the national or local septic tanks;
6. *Extra:* define and analyze relationships between parameters of the tank (content) and user practices (the type of anal cleaning materials, connected to greywater vs blackwater);
7. *Extra:* monitor the fluctuations of the water content and specific gravity (depending on the depth of measurements or seasonal/diurnal fluctuations) of different households.

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A

Background information on sludge accumulation rates

A.1. Summary of studies that assess sludge accumulation rates

Several studies assessed the accumulation of sludge. In this section, an overview of those studies is given, which is also based upon an overview of Nakagiri et al. (2015), who provided a broad overview of the actual filling rates that are noted in the literature on pit latrines. The studies are included in table A.2. Different studies focus on different variables, such as the number of users, materials put in system, design, geophysical or climatic factors.

Studies focused on the correlation between the accumulation rate and the number of users show contradicting results. Some studies show that the accumulation increases with the number of users, while others say the opposite (Bakare, 2014), (Still et al., 2012). The studies of Still et al. (2012) and (Buckley et al. (2008) show that the filling rate almost doubles when users place rubbish in the system. In the study of Brouckaert et al. (2013) a simple mass balance of pit latrine filling was developed. Al Momani (2015) and Nnaji and Agunwamba developed a model for the accumulation in septic tanks.

It is also reported that the rate of filling is highly dependent on the degradation processes that occur within the system over time. Studies show that the process of decomposition is largely aerobic and anaerobic. However, the degradation relies mostly on the occurrence of the anaerobic process. (Buckley et al., 2008)

Table A.1: Published guidelines for emptying frequencies of OSS systems

Country	Type of containment			Advised emptying frequency
Australia (Griffiths et al., 2010)	Septic tank			1-5 years
Australia (South) (Government of SA, 2013)	Septic tank			4 years
	Annual sludge/scum accumulation (L/y)			
		<5000		4
		5.000-10.000		2
		>10.000		1
Canada (Health Canada, 2010)	Septic tank			3-5 years or 1/3 of tank full
Denmark (Thomsen, 2016)	Septic tank			1 year
England (Council of Dean District, 2016)	Septic tank			1 year
France (Government of France, 2011)	OSS system			max 1/2 of tank full
France (Government of France, 2019)	*Type of tank (primary + secondary)*	*Amount of people*	*Volume (m^3)*	
	Model FR4/1800	4	1.83	8 months
	Model FR4/3500	4	3.5	4 years
	Model FR5/2350	5	2.35	8 months
	Model FR5/3200	5	3.22	28 months
	Model FR5/4100	5	4.11	4 years
	Model FR6/3400	6	3.36	22 months
Hong Kong (EPD HK, 1990)	Septic Tank			thickness of sludge >300 mm or 1/4 of overall water depth
India (Governmental of India, 2013), (Luthra et al., 2019) (Government of India, 2017)	OSS system			2-3 years
Ireland (EPA Ireland, 2020)	Septic tanks			1 year or level of sludge on the bottom >400 mm
Ireland (EPA Ireland, 2013)	*Amount of people*	*Frequencies for tank volumes 3 / 3.5 / 4 m^3*		
	1			9.6 / 11.3 / 13 years
	2			4.5 / 5.4 / 6.2 years
	3			2.8 / 3.3 / 3.9 years
	4			2.0 / 2.4 / 2.8 years
	5			1.4 / 1.8 / 2.1 years
	6			1.1 / 1.4 / 1.6 years
	7			0.8 / 1.1 / 1.3 years
Japan (Hashimoto, 2015)	Johkasou			1 year
New Zealand (Wellington region (Wellington Regional Council, 2000)	Septic tank			Crust layer >300 mm Sludge <200 mm
South Africa (Ethekwini, 2014)	Septic Tank			5 years
United States (USEPA, 1999)	Aerobic tanks			1 year
	Borda (settler + baffled reactor)			Settler: 2 years; Baffler: 5 years
	Cesspool			2-10 years
	Dry pits			2-6 years

A.2. Published guidelines for sludge accumulations rate

The sludge accumulation rate determines the emptying frequency. Table A.1 shows that the advised emptying frequency varies among different countries. Some countries, such as Ireland or France, give recommendations depending on tank size or the number of people users. Other states provide a recommended emptying frequency in a range. For example, the government of the United States advise an emptying rate of 2 to 10 years for a cesspool. Also, India emptying septic tanks every 2 years. Other countries give a recommendation with a time constraint of the thickness of the sludge. Literature review show a emptying levels ranging between 30 and 50% ((Beven and Binley, 1992), (Gray, 1995), (Weibel et al., 1955).

Table A.2: Summary of a studies assessing accumulation of sludge with different variables of interest

Author	Variable of interest	Study or experimental approach	Observations
Al Momani (2015)	Septic tank modelling	Developing and testing a simple mass balance	Correlation of R^2 >0.88 with models developed by Weibel et al. (1955) and Bounds (1995)
Bakare (2014)	Amount of users	Analysis of almagamated data documented by Still et al. (2012)	No correlation (Pearson correlation coefficient of 0.203) between the amount of users and the rate of accumulating sludge
		Field observations and measurements	Higher amount of users lead to a decreasing sludge accumulation rate
	Degradation	Laboratory testings on pit latrine samples	50 to 70% reduction of sludge in matter added to the pit
	Increasing moisture	Laboratory batch experiments on pit latrine content	Limited conclusions that more moisture reduced the rate of sludge accumulation.
Banks (2014)	Black soldier fly larvae	Laboratory experiments on content of latrines	The pit content possibly reduces
Brouckaert et al. (2013)	Pit Latrine Modelling	Simulating and testing a model for the sludge behaviour	Non-biodegradable additives influence the filling of pits substantially.
Buckley et al. (2008)	Increasing moisture	Laboratory testings on pit latrine samples	Gas production increases significantly
	Higher Alkalinity	Laboratory testings on pit latrine samples	Anaerobic conditions do not statistically increase the gas production rate
	Using additives	Laboratory testing on content inpit latrine	Indefinite results
Foxon et al. (2009)	Additives	Laboratory testings on content in pit latrine	The effect of mass loss is moderate
Jere et al. (1998)	Spore forming bacteria	Experiments in latrines	Reduction of pit content is significant
Kassam (2012)	Earthworm	In-lab experiments	Amount of human excreta reduces
Lossing et al. (2010)	Solid and site characteristics	In-field observations and statistical analysis	Water usage per capita should be used to predict sludge and scum accumulation
Nnaji and Agunwamba (2012)	Septic tank modelling	Developing and testing a simple mass balance model	Correlation of R = 0.985 between measured accumulation and model results
Norris (2000)	Seasonal variation	In-field observations and measurements	Sludge accumulation is similar through different seasons
Philip et al. (1993)	Septic tank emptying	In-field observations and biochemical study	Optimal reduction of sludge volume after 2.5 - 3 years
Still et al. (2012)	Number of users	In-field observations and measurements	A decrease in per capita filling rate with an increase in number of users.
	Different waste	Monitoring and sorting of pit content	Adding waste to a pit double the accumulation rate
Strande et al. (2018)	Faecal sludge Q and Q	Analysis of documented SPA-DET and In-field observations	Wide range of accumulated faecal sludge calls for context specific estimates
Taljaard et al. (2005)	Bio Additives	In-lab experiments of content of pit latrines	Usage of biological products not feasible
Tay (1982)	A settling model	Developing a settling model based on settling characteristics	Chemical additions decreases the half-removal time of suspended solids.
Todman et al. (2015)	Seasonal variation	In-field observations and measurements	The observed level of the pit content increased significantly during the wet period.
	Pit Latrine Modelling	Modelling filling in pit latrine based on model from Brouckaert et al. (2013)	Amount of water that enters the tank and accumulates affects the filling rate
Wagner et al. (1958)	Degradation		Well set-up degradation can reduce the volume in wet pits up to approximately 80%

B
Expert elicitation

B.1. Elicitation protocol

Expert elicitation of hazardous events of on-site sanitation systems
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Thank you for taking part in this expert judgment evaluation. Please read the following document carefully before filling in your responses. The document will give you an introduction about the research, the method, the elicitation format and hazardous events. The protocol uses elements from the course *Decision Making Under Uncertainty: Introduction to Structured Expert Judgment* of DelftX from Dr T. Nane.

1. Introduction

On-site sanitation systems have recently been acknowledged as a long-term sustainable solution to deal with faecal matter (Ward et al., 2019). Though, to guarantee the safety of all users and prevent people from being exposed to hazardous events, proper operation and maintenance of the OSS systems are of significant importance. This study focuses on the identification, prediction and prevention of **generic** and **non-site-specific** hazardous events for on-site sanitation systems.

The objective of this survey is to prioritise the hazardous events for on-site sanitation systems using structured expert judgment. Structured expert judgment is a tool that has been used in a variety of studies to supplement shortages of data, for example, studies that calculate the risks of power plants or the chances that aliens invase our planet.

Structured expert judgment is an accepted tool in risk analysis for supplementing data shortfalls and quantifying uncertainty. A variety of studies regarding, for example, risks from nuclear power plants and risks of invasive species, used structured expert judgment (Cooke and Goossens, 2004).

The combination of responses from all experts with the calibration variables are treated as statistical hypotheses, that maximises the statistical accuracy and precision. The elicitation involves by specifying percentiles of uncertain quantities, as illustrated on the next page.

2. Elicitation example
Suppose you are presented with the following uncertainty quantity: globally, the number of new daily cases of coronavirus on the 2nd of June 2020. You need to quantify your uncertainty by specifying ranges of your subjective uncertainty.

- Realistically, what do you think is the **lowest** possible number of new daily cases of coronavirus on the 2nd of June in 2020?
- Realistically, what do you think is the **highest** possible number of new daily cases of coronavirus on the 2nd of June in 2020
- Realistically, what is your **best** estimate of the possible number of new daily cases of coronavirus on the 2nd of June in 2020?
- How **confident** are you that the **interval** you created, from lowest to highest, captures the true amount of new daily cases of on the 2nd of June in 2020 (give a number between 0 and 100

Suppose you respond, as shown below:

- Realistically, what do you think is the **lowest** possible number of new daily cases of coronavirus on the 2nd of June in 2020? 60,000
- Realistically, what do you think is the **highest** possible number of new daily cases of coronavirus on the 2nd of June in 2020? 100,000
- Realistically, what is your **best** estimate of the possible number of new daily cases of coronavirus on the 2nd of June in 2020? 75,000
- How **confident** are you that the **interval** you created, from lowest to highest, captures the true amount of new daily cases of on the 2nd of June in 2020 (give a number between 0 and 100%)? 90

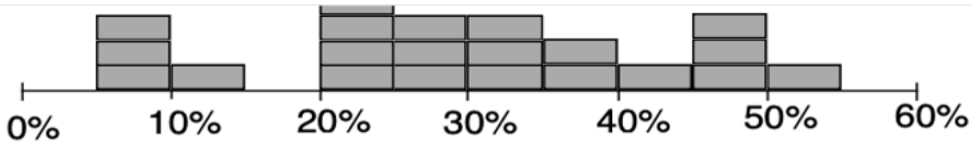
Concluding from your answers, you believe there is a 90% chance that the true value lies between 60,000 and 100,000. Also, you believe that the median of your estimate is 75,000.

Someone who is a reliable assessor is **statically accurate** and **precise**. Statistically accurate means someone who captures the real values with correct relative frequencies. Precision means that the distribution (how far apart the highest and lowest estimates are) is narrow.

Measuring statistical accuracy requires the correct values for a set of assessment. In the above question, the correct value is 115,7053 (worldometers.info). This value falls above the expert's reported 90% confidence interval. If the estimates are statistically accurate and all indicated with in a 90% confidence interval, then, in the long run, 10% of the answers should fall outside this interval. Similarly, 90% of the response should fall inside the ranges.

3. Overconfidence biases while making judgments about uncertainty
There is strong evidence that shows that experts (not only laypeople) often show overconfidence when making probabilistic judgements (O'hagan, 2019). They produce probability distributions that are too narrow. Even though this problem in acknowledge, your judgment is still useful for us. The underneath example explains the bias of overconfidence further.

In a study (Morgan et al., 1990), a well-educated group was asked to make a judgment about large quantities, for example, the length of the Chinese Wall. After that, the researchers asked the respondents to show a 98% confidence; this means that the correct values should be at least in this interval. The percentage of time that someone gave an answer which was outside the 98% confidence interval should have been 2%. The figure below shows the results of the study. Each box represents a separate study. The position of the x-axis shows the percentage of respondents where the estimates fall outsides the 98% confidence interval (e.g. the right-most box shows a study where 50% of the respondents made an assessment outside the 98% confidence interval). In the majority of the studies, more than 20% of the estimates fall outside the 98% confidence interval.



Two final notes:

1. **Do not feel unconfident to use wide distributions**. In guess assessment, the precision is less relevant than the statistical accuracy. The precise but statistically inaccurate performance gives little information. On the other hand, non-precise but statistically accurate performance shows the size of the uncertainties.

2. **Do not feel unconfident when know little about a specific questions or topic.** You will still be a qualified assessor. If you have limited knowledge about a topic, the percentiles of you assessment should be far apart from one another. Other experts that know more, without giving up the width of the accuracy, will exert more influence on the results. If there are no experts that give more precise answers, this shows the greatness of the uncertainty, which is crucial information.

4.Background information septic tank systems

A septic tank is a watertight chamber, typically made of concrete, fiberglass, PVC or plastic (Tilley, 2014). A septic tank on-site system should have three components:

- the septic tank - within the septic tank, settling and anaerobic treatment occur. These processes reduce the solids and organic materials of the incoming sewage. The pathogen removal in a well-function tank is only moderate. The outflow from the septic tank is known as septic tank effluent; and
- a drainage field – for example, absorption trenches comprised of pipes and gravel etc. The septic tank effluent is transported by pipes to the drainage field; and
- the subsurface or soil. The liquid from the drainage field (known as leachate) drains into the subsurface or soil below the drainage field. Within the subsurface, the leachate undergoes further in-situ treatment as part of its ultimate release to the environment or groundwater.

NB: in the survey, the underneath table was shown on every page that refers to the table. In this report, the table is only shown once

			Severity			
		Insigificant *1*	*Minor* *2*	*Moderate* *4*	*Major* *8*	*Catastrophic* *16*
Likelihood						
Very likely	*1*	1	2	4	8	16
Unlikely	*2*	2	4	8	16	32
Possible	*3*	3	6	12	24	48
Likely	*4*	4	8	16	32	64
Almost certain	*5*	5	10	20	40	80
Risk score R = (L) x (S)		< 6	6-12		12-32	32 <
Risk level		Low risk	Medium risk		High risks	Very high risks

5. Calibration questions
These calibration questions determine the weighting scores for each expert. Therefore, please use your best individual estimate.

Question 1
Assuming the drainage field is in a sand or loam material, and there is no lateral movement of liquid, what would be a typical safe vertical distance (in metres) from the bottom of the drainage field to the highest groundwater table to remove most pathogens?

- Realistically, what do you think is the **lowest** safe vertical distance (in metres) from the bottom of the drainage field to the highest groundwater table to remove most pathogens?
- Realistically, what do you think is the **highest** safe vertical distance (in metres) from the bottom of the drainage field to the highest groundwater table to remove most pathogens?
- Realistically, what is your **best** estimate for the safe vertical distance (in metres) from the bottom of the drainage field to the highest groundwater table to remove most pathogens?

Question 2
Again, assuming the drainage field is in a sand or loam material, and there is no lateral movement of liquid, what would be a typical safe vertical distance (in metres) from the bottom of the drainage field to the highest groundwater table to remove most pathogens?

- Realistically, what do you think is the **lowest** safe amount of travel days from the absorption trench needed for viruses to be removed?
- Realistically, what do you think is the **highest** safe amount of travel days from the absorption trench needed for viruses to be removed?
- Realistically, what do you think is the **best** estimate for a safe amount of travel days from the absorption trench needed for viruses to be removed?

Question 3
What is the typical target retention time (in hours) of liquid in a septic tank serving one to two households

- Realistically, what do you think is the **lowest** typical target retention time (in hours) of liquid in a septic tank serving one to two households?
- Realistically, what do you think is the **highest** typical target retention time (in hours) of liquid in a septic tank serving one to two households?
- Realistically, what do you think is the **best** estimate for a typical target retention time (in hours) of liquid in a septic tank serving one to two households?

6.Expert elicitation

Question 1: Groundwater pollution
Leachate of wastewater from a septic tank system to the subsurface can lead to groundwater pollution. Several causes can contribute to the potential of groundwater contamination:

- a drainage field that is working properly but is in an unsuitable location;
- the design of the drainage field is inadequate; and/or
- a high density of septic tank systems in one area.

Inorganic materials, bacteria, parasitic protozoa, viruses, helminths and vector related diseases can be released to the groundwater, which can cause health effects.

Consider the risk matrix underneath *(here in the table of part 4 of this expert elicitation)*. This semi-quantitative risk matrix evaluates risks based upon severity and likelihood. Please give the following estimates of risks taking into account your experiences in the places where you have done most of your work:

1. **Realistically, what do you think is the *lowest* plausible risk that groundwater pollution from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
2. **Realistically, what do you think is the *highest* plausible risk that groundwater pollution from the containment of septic tanks will lead to health effects (Enter a value from the matrix)**?
3. **Realistically, what is your *best* estimate for the plausible risk that groundwater pollution from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
4. **Feel free to share your comments below.**

Question 2: local water course pollution
Local watercourses can be at risk of contamination due to the following reasons:

- a drainage field is absent, inadequate or blocked so that the septic tank effluent drains ultimately unfiltered to a watercourse;
- the tank is full of sludge so that unsettled solids flow out of the tank, which can end up in a watercourse;
- deliberate overflow connection made; and/or
- the proliferation of septic tank systems discharging to land which quickly drains to a watercourse.

Inorganic materials, bacteria, parasitic protozoa, viruses, helminths and vector related diseases can be released to local water courses, which can cause health effects.

Consider the risk matrix underneath *(here in the table of part 4 of this expert elicitation)*. This semi-quantitative risk matrix evaluates risks based upon severity and likelihood. Please give the following estimates of risks taking into account your experiences in the places where you have done most of your work:

1. **Realistically, what do you think is the *lowest* plausible risk that local water course pollution from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
2. **Realistically, what do you think is the *highest* plausible risk that local water course pollution from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
3. **Realistically, what is your *best* estimate for the plausible risk that local water course pollution from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
4. **Feel free to share your comments below.**

Question 3: backing-up of sewage
Backing up of sewage means that the sewage comes back up the inlet pipe and causes an overflow upstream of the tank due to the following reasons:

- sagging or blocked inlet drains; and/or
- full tanks.

If there is an overflow upstream, people could be exposed to sharp objects, malodours, inorganic materials, bacteria, parasitic protozoa, viruses, helminths and vector related diseases, which can cause health effects.

Consider the risk matrix underneath *(here in the table of part 4 of this expert elicitation)*. This semi-quantitative risk matrix evaluates risks based upon severity and likelihood. Please give the following estimates of risks taking into account your experiences in the places where you have done most of your work:

1. **Realistically, what do you think is the *lowest* plausible risk that backing-up of sewage from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
2. **Realistically, what do you think is the *highest* plausible risk that backing-up of sewage from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
3. **Realistically, what is your *best* estimate for the plausible risk that backing-up of sewage from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
4. **Feel free to share your comments below.**

Question 4: solids discharged from the tank
When solids in the tank are not able to settle sufficiently, the solids can flow out of the tank in the septic tank effluent due to the following reasons:

- the tank is full; and/or
- the tank is undersized or inefficient.

When solids are discharged from the tank, people could be exposed to sharp objects, malodours, inorganic materials, bacteria, parasitic protozoa, viruses, helminths and vector related diseases, which can cause health effects.

Consider the risk matrix underneath *(here in the table of part 4 of this expert elicitation)*. This semi-quantitative risk matrix evaluates risks based upon severity and likelihood. Please give the following estimates of risks taking into account your experiences in the places where you have done most of your work.

1. **Realistically, what do you think is the *lowest* plausible risk that the discharge from solids from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
2. **Realistically, what do you think is the *highest* plausible risk that the discharge from solids from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
3. **Realistically, what is your *best* estimate for the plausible risk that the discharge from solids from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
4. **Feel free to share your comments below.**

Question 5: surface flooding
Surface flooding means that the sewage and the suspended solids are overflowing the surface downstream due to the following reasons:

- sagged or blocked inlet drains;
- blocked or inadequate drainage fields; and/or
- the tank is full of sludge.

When solids are discharged from the tank, people could be exposed to malodours, bacteria, parasitic protozoa, viruses, helminths and vector related diseases, which can cause health effects.

Consider the risk matrix underneath *(here in the table of part 4 of this expert elicitation)*. This semi-quantitative risk matrix evaluates risks based upon severity and likelihood. Please give the following estimates of risks taking into account your experiences in the places where you have done most of your work.

1. **Realistically, what do you think is the *lowest* plausible risk that surface flooding from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
2. **Realistically, what do you think is the *highest* plausible risk that surface flooding from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
3. **Realistically, what is your *best* estimate for the plausible risk that surface flooding from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
4. **Feel free to share your comments below.**

Question 6: Odours
Unpleasant odours can be caused by:

- inadequate ventilation of drains or tank; and/or
- a blocked or inadequate drainage field.

Consider the risk matrix underneath *(here in the table of part 4 of this expert elicitation)*. This semi-quantitative risk matrix evaluates risks based upon severity and likelihood. Please give the following estimates of risks taking into account your experiences in the places where you have done most of your work.

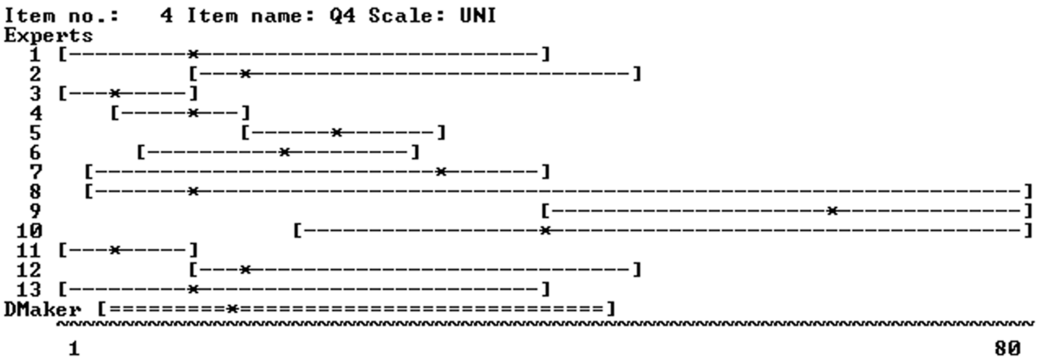
1. **Realistically, what do you think is the *lowest* plausible risk that odours from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
2. **Realistically, what do you think is the *highest* plausible risk that odours from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
3. **Realistically, what is your *best* estimate for the plausible risk that odours from the containment of septic tanks will lead to health effects (Enter a value from the matrix)?**
4. **Feel free to share your comments below.**

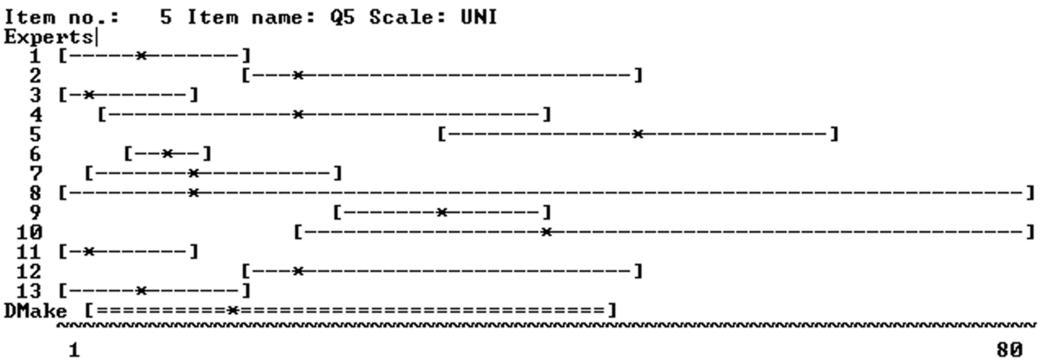
Thank you!
Thank you very much for taking part in this survey. If you have any questions regarding this survey, please contact me at elm.wesseling@gmail.com
If you like, please give some information about your name, profession, experience with sanitation and country of origin.

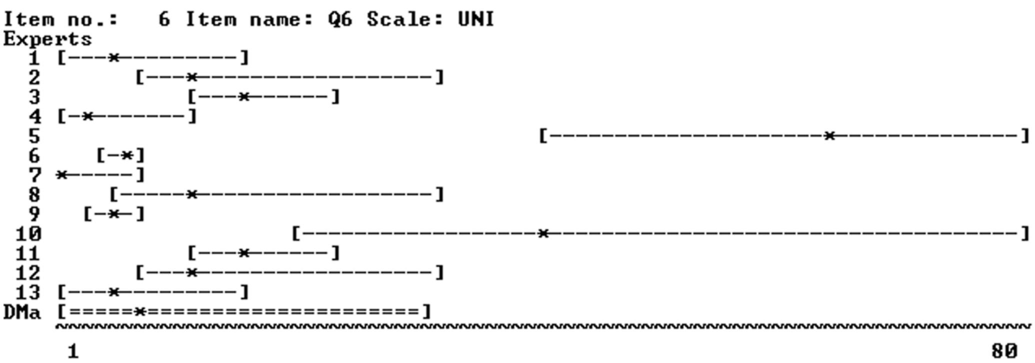
B.2. Results per question per expert

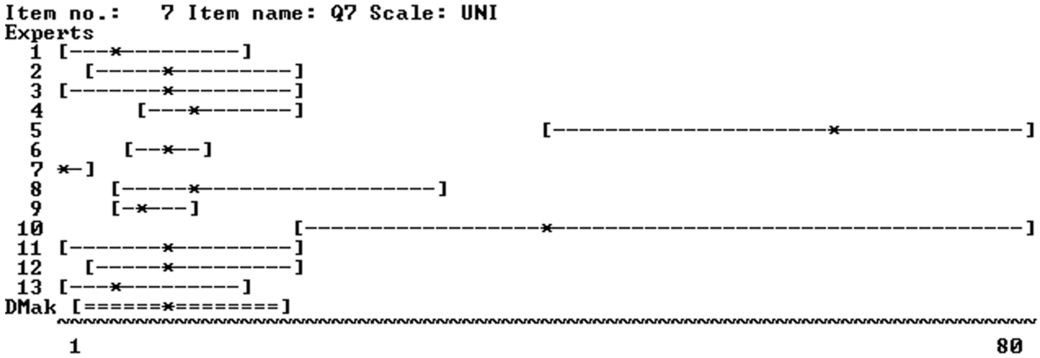
The following figures show the results from the expert elicitation per expert. The item numbers four to ten correspond to the questions one to seven of the expert elicitation, shown in the above section.

4. Groundwater pollution
5. Local water course pollution
6. Backing-up of sewage
7. Solids discharged from tank
8. Surface flooding
9. Odours
10. Tank full/tank lifts





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9
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12
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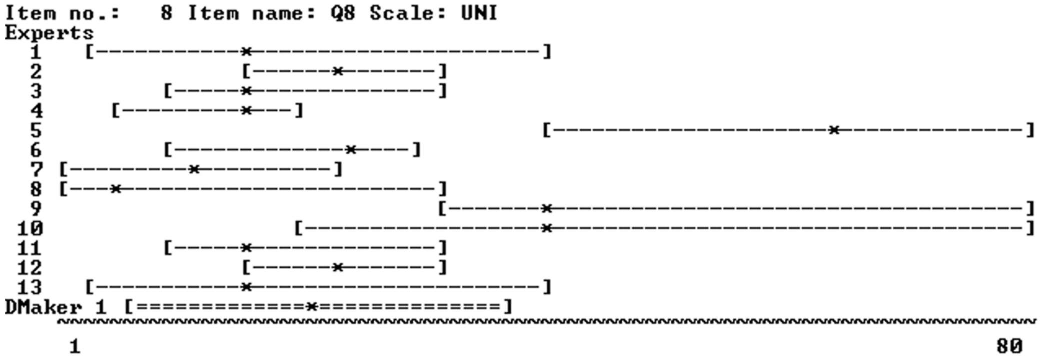
DMak
1
80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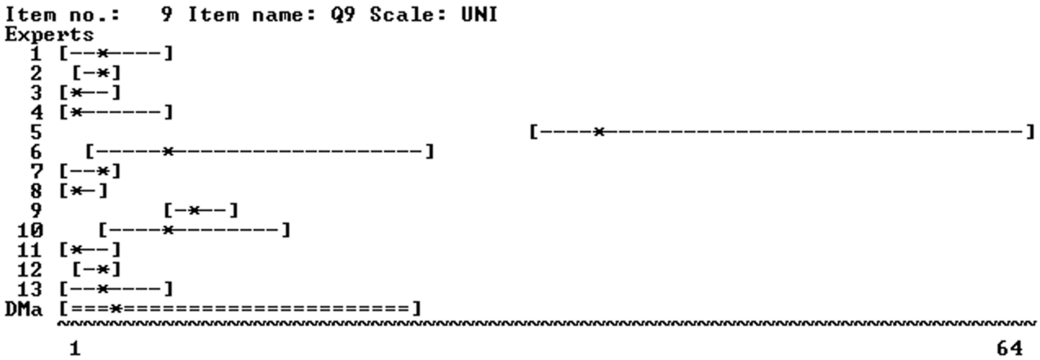
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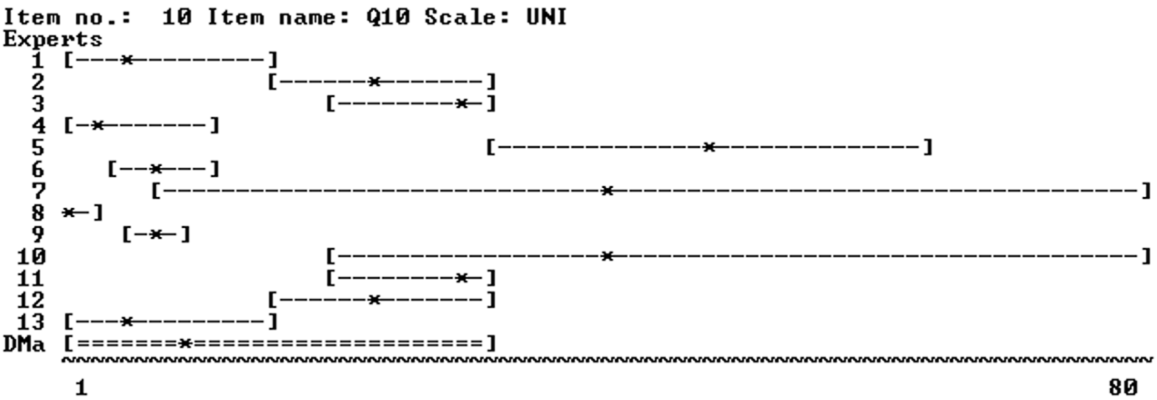
7
8
9
10
11
12
13
DMa
1
64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4
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6
7
8
9
10
11
12
13
DMa
1
80

B.3. Extra information from survey

Table B.1: Extra information extracted from survey

Question	Information
Groundwater pollution	*"Where the septic tank and leach field are properly constructed and well maintained, the risks are negligible (1). But where the setting is inappropriate (as in the three bullet points i.e the septic tank and leach field are poorly constructed and maintained) the risks could be very high and contribute to a health outbreak." (Expert 7)* *"Septic tank effluent contains high viable pathogen concentrations." (Expert 8)"* *"a) most septic tanks I have seen do not have a drainage field but a soakaway, ie more point infiltration than field infiltration b) the risk of health effects is much more influenced by the water supply: where people live of (hand dug) shallow wells (<15m) the health risks are higher than where boreholes are drilled (>40m); and health risks are minimal where boreholes are out of town and water is pipes to the people." (Expert 10)* *"Depth of septic tank and water table level."(Expert 11)* *"Septic tanks are sanitation hazards." (Expert 12)* *"This depends on whether people are getting their drinking water from a shallow well and the distance to the drain field. I would consider the lateral plume length not just groundwater flow."(Expert 13)* *"In urban Maputo, I think the bigger risk from septic tanks results from hygienic pit emptying. The drinking water is quality is quite good." (Expert 16)*
Backing-up of sewage	*"Back-log is possible is maintenance is falling short and design is not robust enough." (Expert 5)* *"I have lived for almost 30 years on septic tanks in Africa and it happened 3 times that the system backed-up. It is a mess to clear it if the pipe is blocked (by roots or poor construction). If you are aware of the health risks dealing with the mess, the risk is low." (Expert 10)* *"People tend to clean up raw waste relatively soon, thus the low impact" (Expert 13)*
Discharge of solids	*"Discharge of solids will lead to the leach field failing and therefore flooding out of the tank or waste on ground surface. Therefore risk level remains high and as per previous scenarios." (Expert 6)* *"If solids flow into the drain field (or soakaway), these will block eventually, leading to a blockage of the tank inlet and a back-up of the inlet pipe. As long as the system is operational and solids flow out of the tank into the drain system, no health risks for people as everything is underground. And if it is not underground, it doesn't matter whether people get in contact with effluent only or mixed wit solids, both are contagious." (Expert 10)*
Surface flooding	*"This is a learning curve. If it happens, folks tend to make repairs and take measures not to flush objects in the future." (Expert 13)* *"From my experience a blocked drainage system or full tank will rather lead to a back-up of the system (i.e. toilet or manholes to septic are overflowing). Only when you temper with the system (i.e. hack a hole into the septic tank), the sewage will spill onto the ground. And people will dig a channel to direct the outflow to a surface water drain." (Expert 10)*

(continued on next page)

	"Again. this is not uncommon. Children are the most affected" (Expert 13)
Odour	*"As far as i know septic tanks must stink as there are anaerobic processes in it which produce GHG CO2 and Ammonia. If you climb into the septic it may kill you (making you unconscious and drowning). But climbs into a septic? (Expert 10)*
Tank lift	*"a) a concrete/masonry septic will fill with groundwater and sewage then overflow which I have seen happen (in Germany!). A plastic septic will lift and the system will back-up or overflow depending on the elevation of the toilet.. (Expert 10)* *"the tank will usually be nearly full all the time with water and therefore not float. The question is a bit unrealistic." (Expert 13)*

C

Risk assessment results

Table C.1: Link between hazards, hazardous events, causes of hazardous events and mitigating measures from risk assessment (ST: septic tank, FL: Full lined storage tank, PL: Partially lined pit, CP: Cess pit/leach pit/leaking septic tank, S: sanitation system users, LC: Local Community, WC: Wider community, SW: sanitation workers)

Hazard	Hazardous events					People group exposed
	Description	Risk level	Cause	Approach to control	OSS system	
Bacteria, parasitic protozoa viruses helmiths and vector related diseases released to the environment	Solids discharged from tank	Medium	Tank full	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC
			Inefficient or undersized tank	Design standards	ST	
			Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	
			Pit collapse	Design standards	PL, CP	
			Deliberate overflow connection	Regulations	ST	
	Surface flooding	High	Tank full of sludge	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC, W
			Inefficient or undersized tank	Design standards	ST, FL, PL, CP	
			Blocked drainage field	Planned Asset maintenance	ST	
			Inadequate drainage field	Design standards	ST	
			Deliberate overflow connection	Regulations	ST	
	Backing-up of sewage	High	Tank full of sludge	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, W
			Inefficient or undersized tank	Design standards	ST, FL, PL, CP	
			Sagging or blocked inlet drains	Planned asset maintenance	ST, FL, (CP)	
	Groundwater pollution	High	Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC, WC, SW
			Sagging or blocket inlet drains	Design standards	ST, FL, (CP)	
			Inadequate drainage field	Design standards	ST	
			Drainage field operating properly but system in unsuitable location	Regulations	ST	
			Proliferation of tanks in sensitive area	Regulations	ST, CP, PL	
			Pit collapse	Design standards	CP, PL	
	Local water course pollution	Medium	Tank full of sludge	Periodically emptying	ST, PL, CP	S, LC, WC, SW
			Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, CP	
			Inadequate drainage field	Design standards	ST	
			Blocked drainage field	Design standards	ST	
			Drainage field operating properly but system in unsuitable location	Regulations, design standards	ST	
			Proliferation of tanks in sensitive area	Regulations, design standards	ST, PL, CP	
			Pit collapse	Design standards	PL, CP	

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Hazard	Hazardous events					People group exposed
	Description	Risk level	Cause	Approach to control	OSS system	
Inorganic material released to the environment	Solids discharged from tank	Medium	Tank full	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC
			Inefficient or undersized tank	Design standards	ST	
			Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	
			Pit collapse	Design standards	PL, CP	
			Deliberate overflow connection	Regulations	ST	
	Backing-up of sewage	High	Tank full of sludge	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, W
			Inefficient or undersized tank	Design standards	ST, FL, PL, CP	
			Sagging or blocked inlet drains	Planned asset maintenance	ST, FL, (CP)	
	Groundwater pollution	High	Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC, WC, SW
			Sagging or blocket inlet drains	Design standards	ST, FL, (CP)	
			Inadequate drainage field	Design standards	ST	
			Drainage field operating properly but system in unsuitable location	Regulations	ST	
			Proliferation of tanks in sensitive area	Regulations	ST, CP, PL	
			Pit collapse	Design standards	CP, PL	
	Local water course pollution	Medium	Tank full of sludge	Periodically emptying	ST, PL, CP	S, LC, WC, SW
			Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, CP	
			Inadequate drainage field	Design standards	ST	
			Blocked drainage field	Design standards	ST	
			Drainage field operating properly but system in unsuitable location	Regulations, design standards	ST	
			Proliferation of tanks in sensitive area	Regulations, design standards	ST, PL, CP	
			Pit collapse	Design standards	PL, CP	
Malodours	Solids discharged from tank	Medium	Tank full	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC
			Inefficient or undersized tank	Design standards	ST	
			Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	
			Pit collapse	Design standards	PL, CP	
			Deliberate overflow connection	Regulations	ST	
	Surface flooding	High	Tank full of sludge	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC, W
			Inefficient or undersized tank	Design standards	ST, FL, PL, CP	
			Blocked drainage field	Planned Asset maintenance	ST	
			Inadequate drainage field	Design standards	ST	
			Deliberate overflow connection	Regulations	ST	
	Backing-up of sewage	High	Tank full of sludge	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, W
			Inefficient or undersized tank	Design standards	ST, FL, PL, CP	
			Sagging or blocked inlet drains	Planned asset maintenance	ST, FL, (CP)	
	Odour	Low	Inadequate ventilation of drains	Planned asset maintenance	ST, FL, CP	S, LC, WC
			Blocked drainage field	Planned asset maintenance	ST	
			Inadequate drainage field	Design standards	ST	
			Pit collapse	Design standards	PL, CP	
			Proliferation of tank discharge to land	Regulations	ST, FL, PL, CP	
			Deliberate overflow connection made	Regulations	ST, (CP)	

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Hazard	Hazardous events					People group exposed
	Description	Risk level	Cause	Approach to control	OSS system	
	Local water course pollution	Medium	Tank full of sludge	Periodically emptying	ST, PL, CP	S, LC, WC, SW
			Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, CP	
			Inadequate drainage field	Design standards	ST	
			Blocked drainage field	Design standards	ST	
			Drainage field operating properly but system in unsuitable location	Regulations, design standards	ST	
			Proliferation of tanks in sensitive area	Regulations, design standards	ST, PL, CP	
			Pit collapse	Design standards	PL, CP	
Sharp objects released to the environment	Backing-up of sewage	High	Tank full of sludge	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, W
			Inefficient or undersized tank	Design standards	ST, FL, PL, CP	
			Sagging or blocked inlet drains	Planned asset maintenance	ST, FL, (CP)	
	Solids discharged from tank	Medium	Tank full	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC
			Inefficient or undersized tank	Design standards	ST	
			Leaking tank	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	
			Pit collapse	Design standards	PL, CP	
			Deliberate overflow connection	Regulations	ST	
	Surface flooding	High	Tank full of sludge	Planned asset maintenance, periodically emptying	ST, FL, PL, CP	S, LC, WC
			Inefficient or undersized tank	Design standards	ST, FL, PL, CP	
			Blocked drainage field	Planned Asset maintenance	ST	
			Inadequate drainage field	Design standards	ST	
			Deliberate overflow connection	Regulations	ST	

D

Numerical equation

This appendix aims to explain the derivation of the equation of Al Momani.

A mass balance approximates the accumulation rate of sludge in septic tank. The mass balance for total solids assumes a constant inlet mass of solids (QC_0) to the tank and a variable concentration of solids in the effluent tank (QC_t). As the sludge accumulates in the tank, the detention time will be reduced as a function of the time, as such that the effluent concentration of solids increases with time. Figure D.1 shows the mass balance of solids in the septic tank

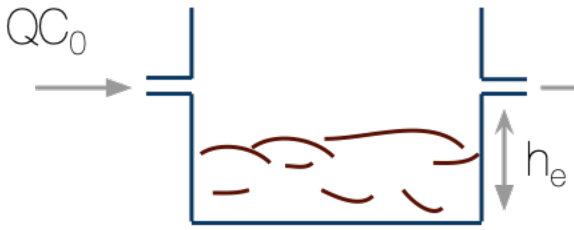

Figure D.1: Mass balance of solids in the septic tank

The mass of sludge dM accumulating in the tank per unit of time is expressed in equation D.1

$$\frac{\mathrm{dM}}{dT} = QC_0 - QC(t) \tag{D.1}$$

The model approaches changes in the mass of solids accumulated in the tank as a function of time as follows:

Mass of solids in the inlet of the tank
- Mass of solids at the effluent of the tank
- Mass of solids decomposed anaerobically
+ Mass of solids generated by bacterial growth

Mass of solids accumulated in the tank

$$\frac{dM}{dT} = QC_0 - QC(t) - k\Delta M + Yk\delta M \tag{D.2}$$

Where M = mass of solids accumulated in the tank at time t, Q = raw sewage flow rate to the tank (m^3/year), C_0 and C_e are the in - effluent concentration of settleable solids (kg/m^3) respectively, ΔM = mass of solids composed anaerobically (kg) and Y = biological yield coefficient (kg/kg), k = organic matter biodegradation rate constant (yr^{-1}).

The concentration of effluent solids increases as sludge accumulates in the tank (Philip et al., 1993); (Al Momani, 2015); (Nnaji and Agunwamba, 2012). The relation between the increase in effluent concentration and the sludge accumulation is described with equation D.3.

$$\frac{dC}{dT} = F\frac{dM}{dt} \tag{D.3}$$

“F is a variable proportionality coefficient and F is related to the slope (γ) of the relationship between sludge accumulation and solids removal efficiency” (Al Momani, 2015). Nnaji and Agunwamba expresses the proportional relationship as $F = C_0/\gamma$.
The differentiation of equation D.2 gives equation D.4.

$$\frac{d^2M}{dt^2} = Q(k - YK - 1)\frac{dC}{dt} \tag{D.4}$$

The inclusion of equation D.3 in equation D.4 gives:

$$\frac{d^2M}{dt^2} = QF(k - YK - 1)\frac{dM}{dt} \tag{D.5}$$

Let

$$\beta = \frac{QC_O}{\gamma}(k - YK - 1) \tag{D.6}$$

Equation D.5 can be rewritten as:

$$\frac{d^2M}{dt^2} = \beta\frac{dM}{dt} \tag{D.7}$$

The integration of D.7 gives equation D.8 with the initial conditions at t = t_e, M_e = C(t_e)Ah_e and at t=t_e, $\frac{dM}{dt} = QC_0 - QC(t_e)$. C($t_e$) is the effluent solids concentration at time t_e, A is the surface of the tank, and h_e is the exit height of the tank.

$$M = C_0Q\chi t + C_0(Ah_e) + \frac{Q\eta}{\beta}C_0(\frac{e^{\beta t}}{e^{\beta\theta_i}} - 1) \tag{D.8}$$

Let

$$\eta = \frac{C_0 - C_e}{C_0} \tag{D.9}$$

$$M = C_0(Ah_e) + \frac{Q\eta}{\beta}C_0\left(\frac{e^{\beta t}}{e^{\beta t_e}} - 1\right) \tag{D.10}$$

To consider the non-biodegradable organic matter in the tank, equation D.10 is adjusted to give equation D.11, which considers also the initial detention time θ_i. χ is the fraction of nonbiodegradable solids and ranges typically between 0.1 to 0.15 (Al Momani, 2015).

$$M = C_0Q\chi t + C_0(Ah_e) + \frac{Q\eta}{\beta}C_0\left(\frac{e^{\beta t}}{e^{\beta\theta_i}} - 1\right) \tag{D.11}$$

To convert the mass of solids to effective volume the density of the sludge is used with equation D.12. Where the SG = Specific gravity of sludge (–), w = water content of sludge (–) and ρ_w is the density of water.

$$\rho_{sludge} = SG\rho_w(1 - w) \tag{D.12}$$

The volume of sludge is calculated with

$$V_{\text{sludge}} = \frac{C_0Q\chi t + C_0(Ah_e) + \frac{Q\eta}{\beta}C_0(\frac{e^{\beta t}}{e^{\beta\theta_i}} - 1)}{1000SG(1 - w)} \tag{D.13}$$

E

Modelling choices and results

E.1. Introduction

The developed model was built as a supporting method to create guidelines on the emptying frequency of septic tanks. The model is an as accurate representation of the real fill rate so that the outcome is as useful as possible. However, to sure that users use the model in a correct and relevant manner, the decisions that were made during the modelling processes need to be understood. This chapter tries to clarify the specific modelling choices based upon the *Guide for Good Modelling Practice in policy support* provided by Nikolic et al. (2019). These choices are scrutinized in the discussion.

E.2. Problem definition

The model will generate a recommendation for the emptying frequency of particular septic tanks. This is different from the current practice where emptying frequency recommendations are created independent of the tank size, the number of users or tank specific characteristics. The modelling question is *What is the effect of tank characteristics and user's practices on the emptying frequency of septic tanks given that the accumulation of sludge follows a mass balance and the values of the parameters are constant in time.* This section tracks the assumptions that were made during the modelling process. Also, the technical requirements which differentiate this model from other sludge accumulation models, are shown.

Modelling question

The performance and safety of septic tanks are dependent on the fullness of a septic tank. However, guidelines on how often to empty septic tanks are mostly formed on an arbitrary basis. Also, scientists have not found a simple method which makes it accessible to determine how fast a septic tank fills and how often a tank should be emptied. Since the fill rate of the septic tank depends on a wide range of factors, it will be difficult to measure all of these elements. Instead, a model which can generate the fill rate using as little in-field measurements as possible can give more well-founded results. Tank owners, tank managers or policymakers could use the results (or the model).

The results of the model can be used for providing tank and user-specific recommendations of the operational and maintenance requirements for users of such OSS systems. Also, it can be used to assess the safe or unsafe status of an OSS system and detect where, on a global scale, most unsafe OSS systems are located and solutions are needed. This could help policymaker makers in their decision-making regarding safe sanitation and eventually, this will contribute to the safeness of septic tanks and thus will contribute to protecting the health of the people in the vicinity of septic tanks.

System boundary definition

This model assesses the accumulation inside a particular septic tank, provided that the model can be used for every size of the tank and every size of household using such tank. People use different definitions for septic tanks. Within this research a septic tank is considered as a watertight chamber, typically made of concrete, fibreglass, PVC or plastic Tilley. A septic tank on-site system should have three components:

- the septic tank: within the septic tank, settling and anaerobic treatment occur. These processes reduce the solids and organic materials of the incoming sewage. The pathogen removal in a well-function tank is only moderate. The outflow from the septic tank is known as septic tank effluent; and
- a drainage field – for example, absorption trenches comprised of pipes and gravel etc. The septic tank effluent is transported by pipes to the drainage field; and
- the subsurface or soil. The liquid from the drainage field (known as leachate) drains into the subsurface or soil below the drainage field. Within the subsurface, the leachate undergoes further in-situ treatment as part of its ultimate release to the environment or groundwater.

The model only focuses on the septic tank. There are no geographical limits regarding the usability of the model.

Modelling question

The modelling question can be formulated using the XLRM framework (figure E.1), that considers the policies, the uncertainties, the model relationships and the performance metrics (Lempert, 2003). The policies are the actions that can be controlled. The model relations describe explicitly the relations between elements in the system. The uncertainties (X) are the elements, which are not influential and out of our control. The performance metrics show the outcomes of interest and the impact of the actions. It also indicates what is measured and how. The diagram in figure E.1 shows the considerations that were made.

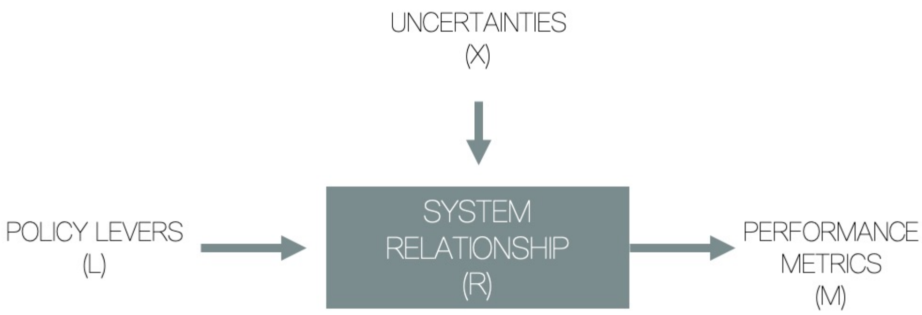

Figure E.1: XLRM frame

Table E.1: XLRM framework

Framework	*Description*
Model relationships *(R)*	The accumulation of sludge follows a mass balance (Equation 5.4)
Uncertainties/planning assumptions *(X)*	Parameter values are constant in time
Policies *(L)*	Tank characteristics and user practices
Performance metrics *(M)*	Expected emptying frequency of septic tanks

The modelling question is as following: *What is the effect of tank characteristics and user's practices on the emptying frequency of septic tank given that the accumulation of sludge follows a mass balance and the parameter values are constant in time?*

Assumption tracking

This section provides all the assumptions that were made during the modelling process, including the reasons for using the assumption.

- the outcome of the model depends on an assumed safe emptying level. By default, a safe emptying frequency is when the tank is for 25% filled with sludge. This assumption is made because there is currently not a globally accepted *safe* emptying frequency. When comparing the different governmental guidelines and the guidelines indicated in the literature, this is the most conservative guideline;

- doing more than two in-field measurements is inefficient and costly. This assumption is made to make the model as feasible as possible so that it can be used by low and high-income countries;
- in literature found extreme values for parameters are representative for the parameter ranges. This assumption is made because there were no better alternatives for usable parameter ranges;
- a Monte Carlo analysis can generate good estimates of the distribution of parameters. There were no distributions of parameters found;
- the calibration of the value of β with other studies generates credible estimates of β;
- the effluent height is always 30 centimetre under the tank height. This assumption was made to simplify the modelling procedure and to avoid the effluent height to be larger than the tank height, which is impossible;
- the effluent concentration is always 20 to 80% of the influent concentration. This is to avoid the effluent concentration to be higher than the influent concentration, which is not possible;
- table 5.3 shows the measured sludge accumulation data of other research studies. These data are assumed to be representative for the accumulation of sludge, because of the limited data that are available in the literature.

Technical requirements

There are several technical requirements and limitations that the model has to meet. Some studies already model the accumulation of sludge, but the requirements of the model differentiate this model from other models.

- limited in-field measurements;
- ability to incorporate different governmental requirements on when to empty the tank;
- usable by different household and tank sizes;
- outcome of the model should be easily translatable into concrete recommendations without the necessity of any coding programs;

E.3. Model

This section clarifies the modelling processes. The section presents the chosen modelling formalism, the conceptual model, the model implementation details and the verification of the model. More details of these steps are also presented in chapter 5.3.

Choice for the modelling formalism

The constructed model is a simplification of the process that takes place in the tank in reality real model. The model chooses a model paradigm of technical design and performance. The model is based on laws of nature, that reviews the mass of faecal sludge that comes inside a septic tank, the part of the faecal mass that is biologically degraded under anaerobic conditions, the part that flows out of the tank, and the remaining part that accumulates inside the tank. The model is used as a prediction of this settling and biophysical processes. Statistical models and data-driven models were considered, however, because of the necessary large required amount of data, this technically designed model based on the performance of a septic tank was assumed more suitable.

Conceptual model description and implementation details

Figure E.2 shows the conceptual model. What the model does, how the model works and what is measured is explained in more details in chapter 5.3.

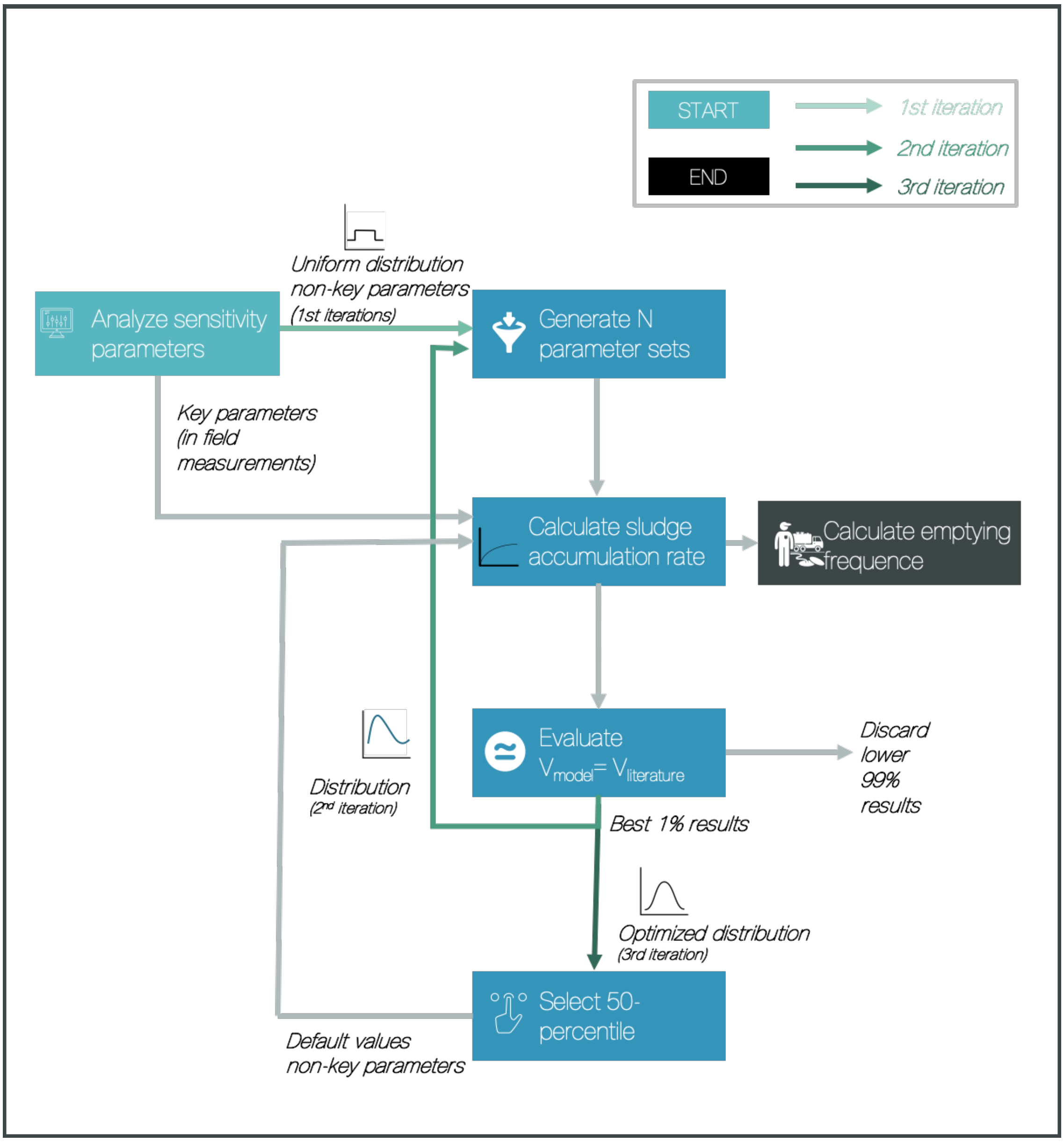

Figure E.2: Schematic overview of the model steps

Model verification

In order to verify whether the model was build right, two verification tests were done. The first test involved using a standardized dataset. The different outcomes were compared with each other and the differences were explainable. The other test is called Extreme Value Testing. The model uses Extreme values to check what happens when the variables have positive or negative infinity values. Also, it considers the parameter values that do not lead to meaningful results. Some of these tests led to the inclusion of some assumptions, such as, that the effluent concentration should always have a value that is less than the influent concentration.

E.4. Input data

The following section describes the selection of input data, the model parametrisation and the handling of uncertainty.

Input data selection

Identify non-key parameters
The sensitivity generates a distinction between the key and the non-key parameters. This analysis uses ranges found in the literature for the water content of settleable solids, the specific gravity of settleable solids, the non-biodegradable part of solids, the influent and effluent concentration of settleable solids and the discharge rate. For the area of the tank, the height of the tank and the raw sewage flow, specifications were used that were found in commercially available tanks.

Distribution of parameter
To draw random parameter samples for the Monte Carlo simulation, data are needed for the distribution of the parameters. Since these data are currently missing, the data are generated via three Monte Carlo samplings (more details available in chapter 5). Boundary conditions are acquired from values in literature. The largest boundary conditions are used to include as many parameter values as possible.

Verification
Secondly, the Monte Carlo analysis verifies the modelled sludge accumulation with actual sludge accumulation. The available measured or actual sludge accumulation data are limited and therefore, a set of data that was published from different research is used.

Model parametrisation

The model describes the behaviour of historical septic tanks in time. This parameterisation is chosen because it can show the nonlinear characteristics of the fillrate of the tank. The non-key parameters (the discharge rate, the area of the tank, the height of the tank, the effluent concentration, the influent concentration, the non-biodegradable parts of the solids and the β (equation D.6) are assumed to be constant in time. In each model run, the time will vary. The model is run by different settings of the water content, specific gravity and volumes of the tank.

The units for the mass is kg, the units for time in years, the units for volume in m^3. Table 5.2 shows the used units as well. Initial data to estimate the value of β are not available. Therefore, the boundary conditions are estimated by calibrating the formula with previous studies (Maunoir et al., 2007), (Kinsley et al., 2005), (Gray, 1995).

Input uncertainty handling

"There are known knowns, known unknowns and unknown unknowns" as described by Hampton et al.. This section lists the uncertainty of the data and model structure.

Data
The uncertainty of the input data is limited since it only uses certain boundary conditions as shown in table 5.1. For the fraction of non-biodegradable solids (χ) there is no uncertainty since the boundary condition is between 0 and 1. Also, for the other used boundary conditions, the used ranges are larger than the found

ranges in literature. This is done to make sure that within the Monte Carlo simulation, all possible combinations are considered. The uncertainty for the data used for validation could be decreased in the future. Because the articles from the used sources were unavailable, the measurement methods could not be checked to estimate the errors. Also, the underlying user and tank characteristics could not be verified. Which, could have created an idea of the topographical and user-specific diversity of the measurements.

Model structure
The model structure has multiple uncertainties. The method of GLUE verifies the values the calculated outcome of the model with the values of literature. Most applications of the GLUE method uses a large data set of time series to validate the outcome of the model. However, since this was not available, we used small data sets. There is an uncertainty in the sensitivity analysis. The sensitivity analysis uses the input of parameter ranges. If these ranges are off, then the sensitivity analysis could indicate the wrong sensitive parameters.

Expected development
In the future, policymakers could include data of the parameters that are from one location and validate the outcome of the model with sludge accumulation measurements of septic tanks from that same area.

E.5. Experimentation and results

The validation of the model concerns the fitness of the model for the purpose for which it was created. This model uses classical fitness measurements, where the model compares the accumulation of sludge with performed measurements experiments of septic tanks. The correlation defines the fitness of the model. However, it would be very useful to validate whether the model would lead to an implementation of the recommendations and thus safer sanitation systems. In that manner, the model should also describe the social elements of the system.

The parameterisation of the fitness of the model is the Pearson correlation factors and resulted in a score of 0.97 with a model from Weibel et al. (1955) and a score of 0.9 with a research from Bassan et al. (2014). The model is fit enough to be used for one part of the intended purpose: to provide recommendations for the emptying frequencies of septic tanks.

Uncertainty handling

Model variability Since this model contains stochastic elements that produce a variable outcome, different model runs will produce different outcomes. The sources of uncertainty come from the boundary conditions in the input data and the uncertainties of the model structures (such as the usage of the method called GLUE) and the random values that are created in the Monte Carlo analyses. To analyse the uncertainty of the model, the following uncertainty analysis plan is executed:

- Model variability analysis executes the model with identical parameter settings and multiple time and compares the outcome. The outcomes of the 50-percentile will be different but should be within a range of 0.05 %. The cause of the difference is because the Monte Carlo sampling draws random samples from firstly, random uniform distribution and secondly from a calculated distribution.
- A local sensitivity analysis shows that the difference of the input variable does not influence the outcome much;
- a global sensitivity analysis shows that the combination of multiple different parameters does not influence the outcome much.

E.6. Sense making and insight

Output data handling

After developing the data, the resulting data represent the emptying frequency. Each data set contains the outcome of emptying frequency for different tank sizes (small/medium/large) and different amounts of users. Within each data set, there is a different output per amount of water content, in a range between 0.75 and 0.95 and specific gravity, in a range between 1.1 and 1.5. All data files are stored in different tabs of a large Spread Sheet.

Output analysis

In the analysis of the output, we expect that the impact of the water content is high. This is because, in the sensitivity analysis, there was found that the water content has a large impact on the emptying frequency. The impact of the specific gravity should also be notable, but not as large as the water content. It is also expected that when the amount of users increases, the emptying frequency decreases. These patterns are clearly visible.

Output visualization

In terms of output visualization, the focus has been on the key message that should be conveyed through these data. This depends on the type of user. For a manager of a large number of septic tanks, the outcomes should be as accurate as possible so that the manager of the septic tank can plan the emptying frequency accordingly. Therefore, a Visual Basic Editor (VBE) excel has been made, where a manager can insert the specific tank requirements in a straight forward user format. The VBA excel shows immediately the emptying frequency for a specific tank. For policymaker, a straightforward recommendation for the local community is more applicable. Therefore, one graph shows the emptying frequency for different tank sizes and different numbers of users. There are different graphs for different settings of water content and specific gravity. Policymaker can choose the relevant settings that apply to their jurisdiction. The chosen metrics that are chosen focus on the emptying frequency that are rounded to half a year, which are more understandable for locals (instead of a recommendation: empty your tank after 2.3 years).

E.7. Emptying frequency plots for different amount of users and tank sizes

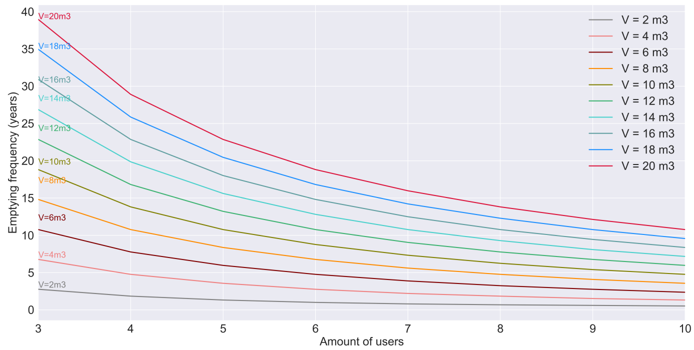

Figure E.3: Emptying frequency recommendation for different users and tank sizes for w=0.8, SG=1.1

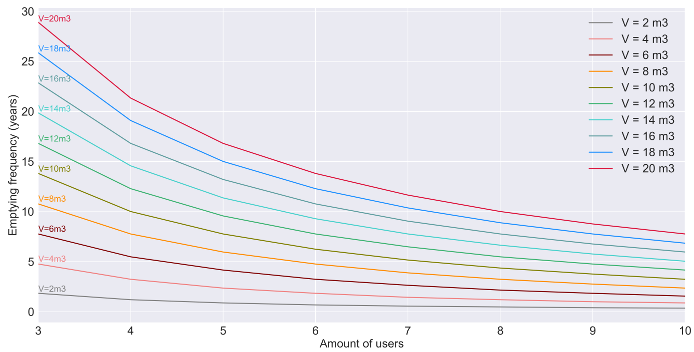

Figure E.4: Emptying frequency recommendation for different users and tank sizes for w=0.85, SG=1.1

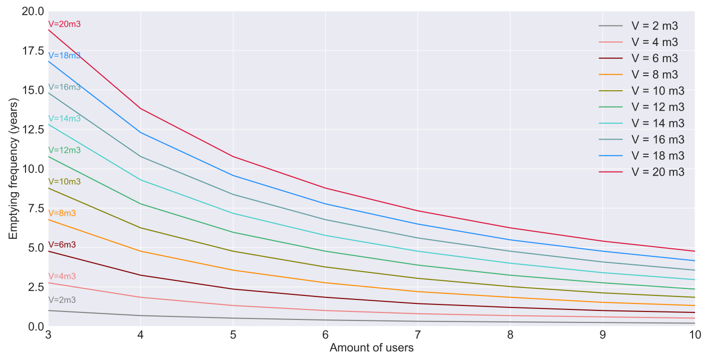

Figure E.5: Emptying frequency recommendation for different users and tank sizes for w=0.9, SG=1.1

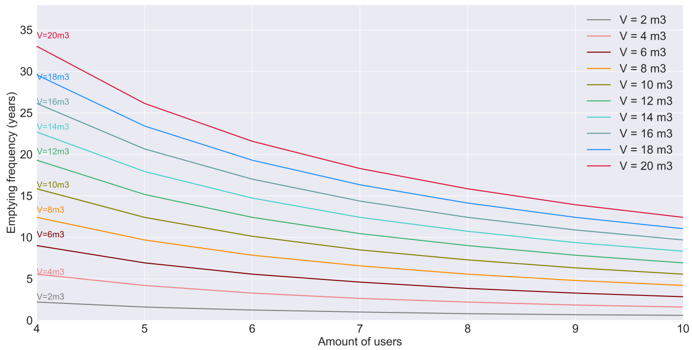

Figure E.6: Emptying frequency recommendation for different users and tank sizes for w=0.8, SG=1.25

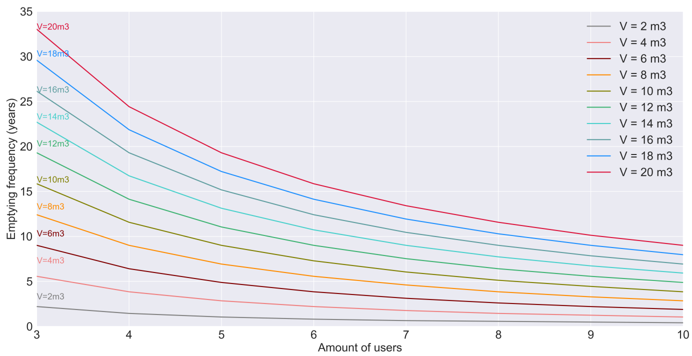

Figure E.7: Emptying frequency recommendation for different users and tank sizes for w=0.85, SG=1.25

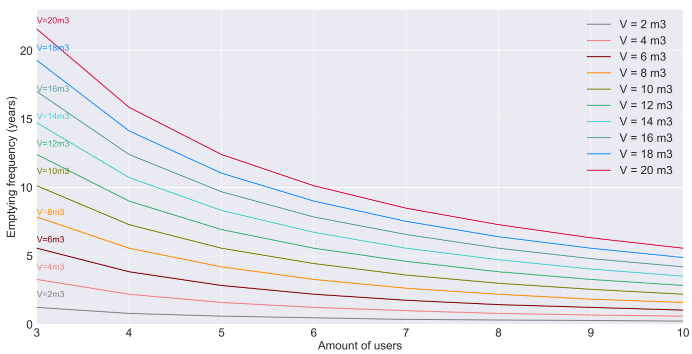

Figure E.8: Emptying frequency recommendation for different users and tank sizes for w=0.9, SG=1.5

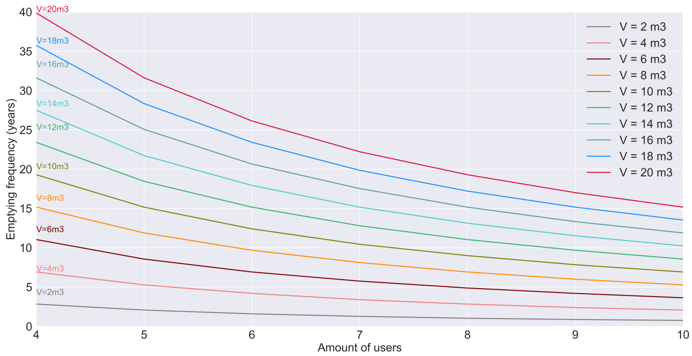

Figure E.9: Emptying frequency recommendation for different users and tank sizes for w=0.8, SG=1.5

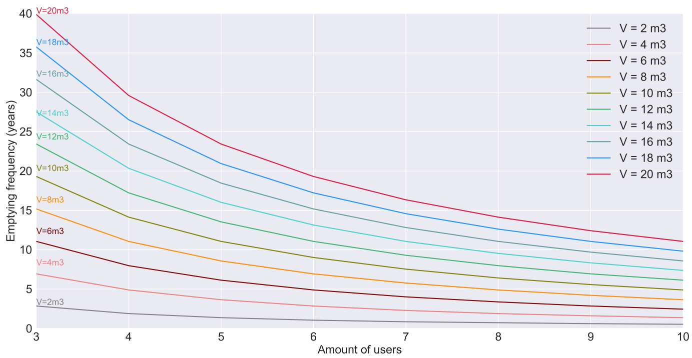

Figure E.10: Emptying frequency recommendation for different users and tank sizes for w=0.85, SG=1.5

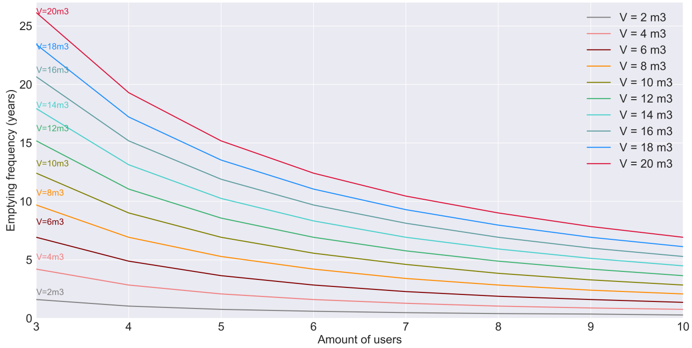

Figure E.11: Emptying frequency recommendation for different users and tank sizes for w=0.9, SG=1.5

F

Water content sludge

F.1. Different types of water in sludge

There are many different quantitative measurements to describe the distribution of water in sludge. This is because the physical properties of water adjacent to the sludge particles surface differ from those of bulk water.

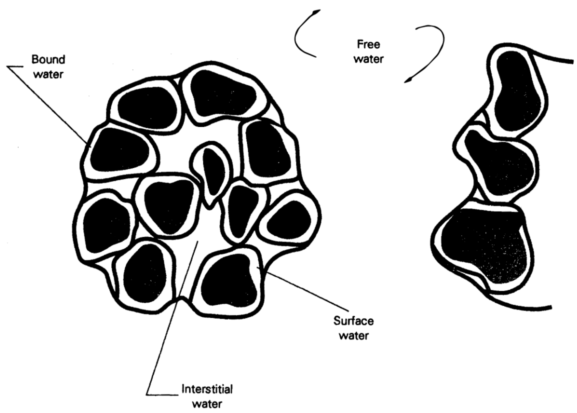

Figure F.1: A conceptual visualization of the moisture distribution in sludge, reprinted from (Tsang and Vesilind, 1990)

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The simplest way to distinguish the various types of water is by dividing water into two parts: bound water and free water. Bound water is held chemically and/or physically onto the flocs. Free water, the remaining water, behaves the same as bulk water and can easily be removed via mechanical means. Heukelekian and Weisberg (1956) refer to the two different kinds of water, “interstitial water which can be forced out by the application of slight pressure, and absorbed water which cannot be removed mechanically except by the application of enormous pressure”. According to this reference, the proportion of these waters depend on the state of subdivision of the particles and the extent to “which the jelly constituents are swollen with water”. The latter type is referred to as “bound” water.

Tsang and Vesilind (1990) use drying curves to distinguish four different moistures: free moisture, interstitial moisture, surface moisture, bound moisture. The moisture distribution in sludge is depicted in a diagram of Tsang and Vesilind (1990) in figure F.1.

Lee and Hsu (1995) state that the bound water content is an operational value and depends greatly on used the evaluation method.

Table F.1: Bound water contents measured via centrifugal settling (CS), expression (EX), drying test (Drying), and DSC tests (DSC). Reprinted from Lee and Lee (1995)

Sludge	CS (kg/kg)	EX (kg/kg)	Drying (kg/kg)	DSC (kg/kg)	W_v (kg/kg)	W_s (kg/kg)	W_i (kg/kg)
$CaCO_3$	1.03	0.02	0.31	0.28	0.72	0.29	0.02
PVC	1.15	0.03	0.09	0.08	1.06	0.06	0.03
GlaI	0.56	0.001	0.013	x	0.55	0.013	0.0
GlaII	0.58	x	0.018	x	0.56	0.018	0.0
GlaIII	0.54	x	0.27	x	0.51	0.027	0.0
GlaIV	0.61	x	0.036	0.041	0.57	0.036	0.0
GlaV	0.60	x	0.047	0.056	0.55	0.046	0.0
$Cu(OH_2)$	x	0.44	1.86	x	x	1.42	0.44
Activated Sludge	x	3.85	6.7	x	x	2.85	3.85

The bound water contents are in kg-bound water/kg-dry solid. Gla: glass powders.
The symbol X indicates that the data are unavailable or the deviation is too large.
Wv, Ws, and Wi refer to interstitial, surface, and internal water content, respectively

F.2. Water content measuring methods

Drying tests

An example of a drying test is shown in figure F.2. In this example, from a research from Deng et al. (2011), the drying test consists of a thermostatically controlled heating oven. Inside the oven was a digital balance. The balance recorded the data automatically by a computer. The sludge can be placed in the oven and dried slowly at 30°C, with controlled humidity by sparging the oven with compressed dry air. The sludge mass is recorded every 10 min until there is no more change in sludge mass. After this process, the sludge sample is heated at a temperature of 105°C for 12 hours to determine the final dried mass.

Brunner (1978) described a drying procedure where a sample of sludge of 100-200 g in a flask is weighted to the nearest 0.1 gram. Subsequently, the sample is dried in the oven for 24 hours at a temperature of 100°C. The water content is calculated with equation F.1.

$$\frac{\text{initial weight - final weight}}{\text{Initial weight}} \cdot 100 \tag{F.1}$$

Brunner (1978) also describes a method using InfraRed Light. 20 to 40 grams of sludge is weighted in an aluminium bowl. Following, the sample is dried on a balance under an infrared lamp until the weight remains constant. Drying takes usually 30 minutes with a distance of 4.5 centimetres. The water content is calculated with equation F.1.

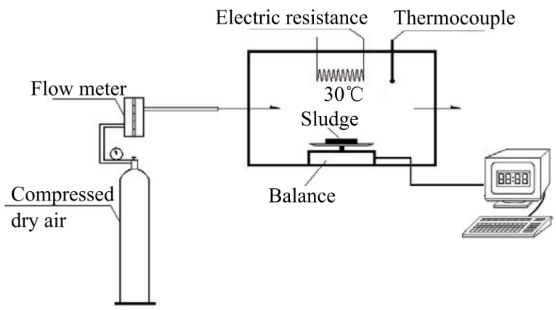

Figure F.2: Example of schematic diagram of drying test, reprinted from Deng et al. (2011)

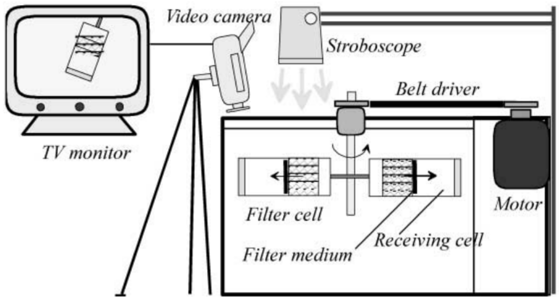

Figure F.3: Diagram of a centrifugal experimental set-up, reprinted from Chu and Lee (2002)

Dilatometry
Dilatometry is a technique which focuses on the measurements of bound water. The theory behind this method is that bound water does not freeze at temperatures below the freezing point temperature of free water. By knowing the amount of total water and the amount of free water, the difference between them is the bound water. The total water is determined by drying a sample at 105°C for 24 hours. The free water is measured by noting the expansion caused by freezing the sludge. Subsequently, the bound water can be calculated (Heukelekian and Weisberg, 1956).

Differential Scanning Calorimetry (DSC)
The thermal behaviour of (different types of) water can be determined during heating or cooling studied by DSC. This method permits direct thermal analysis for phase changes of free water. The DSC curve gives the heat evolved or absorbed during a phase transition (Lee et al., 1975). The DSC test assumes that the bound water will not be free at a threshold temperature, T_{sh}. The heat absorbed in the heating stage is equal to the latent heat required for freezing free water. (Lee et al., 1975), (Lee and Lee, 1995).

Centrifugal settling
Centrifugal settling method can find the "wet solid", which contains only the solid phase and the bound water. This method measures the "packed cell volume" by extrapolating the sludge sediment height to $N \longrightarrow \infty$. The equilibrium sediment height varies linearly with the N^{-1} when rotational speed ranges from 500 to 3500 rpm. Since the centrifugal force should be infinitely large and because the bound water is recognised as the portion which is hard to remove via mechanical means, it is proposed that the equilibrium with infinite rotations contains only the solid phase and the bound water.

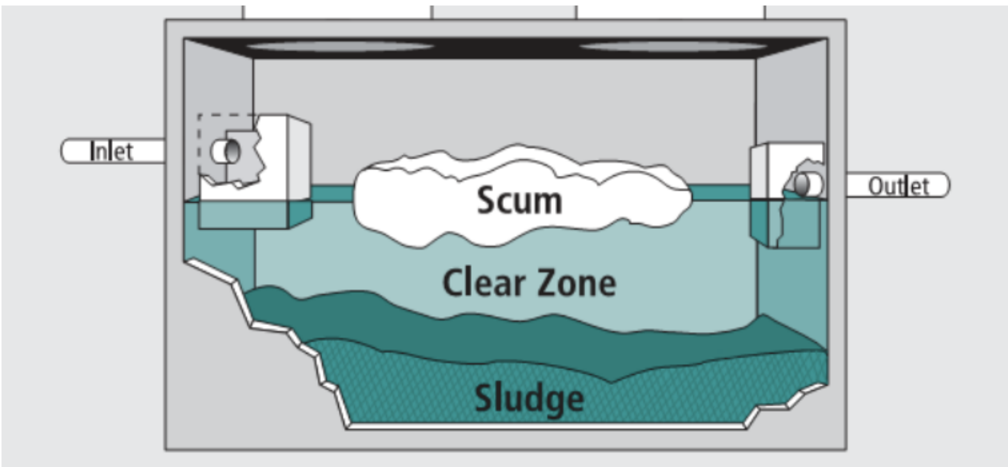

Figure F.4: Different layers inside the septic tank

The centrifugal test set-up is depicted in figure F.3. In this image, a cell with filter is rotated on a belt driver with a speed ranging from 41.9 and 104.7 Hz (400-1000 rpm). All suspended water is filtered out through the media and accumulates in the filter cell (Chu and Lee, 2002). In this study, it is concluded that the rotational speed affects the dewatering efficiency. Chu and Lee (2002) also show that cationic polyelectrolyte flocculation has a large impact on the dewatering efficiency.

Expression Test
The expression test is based upon the assumption that the residual water content in a consolidated cake, subjected to an extremely large force, is the bound water content. When the applied extremely large force increases, the residual moisture decreases. (Lee et al., 2006).

Different sludge layers
Within a septic tank, different layers can be distinguished as shown in figure F.4. The settled solid is defined as sludge, the floated solids as scum and the liquid layer as the clear zone. Research by Chagas et al. (2013), who studied different characteristics and heights of scum and sludge layers, reported that the proportional heights occupied by each layer inside a septic tank vary in a wide range. “The sludge layer represented about one third or less of the total content in most cases”.


State