Modelling Viral Emissions from Pit Latrines to Groundwater

MSc Thesis

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WAGENINGEN UNIVERSITY & RESEARCH

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Contents

Abstract

Pit latrines are widely used as the primary mode of sanitation in many developing countries. With the rapid rate of urbanization, pit latrine use continues to increase and there is growing concern about the negative impacts on groundwater quality, which many people rely on as their main source of drinking water. Studies have associated groundwater contamination with pit latrine use, and several studies have suggested setback distances of wastewater systems from drinking water wells; however, the transport processes of pathogens from pit latrines to groundwater have not been comprehensively explored and quantified. The objective of this study is to develop a conceptual model to assess virus emissions from pit latrines to groundwater. Literature reviews were conducted to determine the current state of knowledge on the processes and available models on virus transport and fate in pit latrines and the vadose zone. Using the available data and parameters obtained from the review, the 1D advection-dispersion equation coupled with virus removal and inactivation rates was used to deduce the log reduction of viruses in pit latrines and the vadose zone. The model was applied to four urban areas in Africa with a high prevalence of pit latrine use and distinct pit latrine and soil characteristics. The results of the model simulation indicate that the initial loading rate of viruses in pit latrines is primarily dependent on the virus prevalence in the specific area, and the total log reduction of viruses increases with the depth of pit latrines and the vadose zone. A pit latrine filled with contents at a depth of 3m can reduce virus concentrations up to 2 log. The model also revealed that virus reduction is greatest in soils with the highest proportion of clay and lowest in sandy soils. A vadose zone composed of clay soils at a depth of 2m reduces virus concentrations by 4 log, whereas sandy soils are only capable of reducing viruses by 0.7 log even at a depth of 200m. The results of a sensitivity analysis show that the removal rate of viruses has the greatest impact on the reduction of viruses in pit latrines and the vadose zone. This study provides a preliminary model for modelling virus transport and fate in pit latrines to groundwater, which can be used as guideline to improve pit latrine and groundwater management, and as a baseline for developing more sophisticated models in the future. As a novel area of research, the study also highlights the need for more research on pit latrine processes and reliable data on model parameters.

Chapter 1: Introduction

Background

Access to safe drinking water and adequate sanitation are crucial for maintaining public health. The number of people that have access to improved sanitation has increased by 14% over the past two decades, but there are still 2.3 billion people that do not have access to basic sanitation facilities (WHO & UNICEF, 2015). Nearly 900 million people consequently resort to open defecation (WHO & UNICEF, 2015). Most of these issues arise in the slums of urban areas where people have little access to basic services such as water and sanitation (Dakpallah, 2011; Mara et al., 2010). Pit latrines are concentrated in urban areas and the continuous rapid growth of urbanization is further deteriorating access to sanitation and clean water, and exacerbating health risks from water contamination (Dakpallah, 2011; Okot-Okumu & Oosterveer, 2010). Fecal contamination of drinking water arising from the lack of sanitation is the primary cause for the widespread of waterborne diseases (Pruss-Ustun & WHO, 2008). Improper disposal of feces contaminates water bodies and causes diseases among people that rely on these sources as their primary drinking water supply (Bartram & Cairncross, 2010; Johnston et al., 2011; Pruss-Ustun & WHO, 2008). Several recent reviews have suggested that providing access to protected water sources and improved sanitation—defined as the hygienic separation of human excreta from human contact (WHO & UNICEF, 2015)—are key factors to reduce the prevalence of diarrheal disease (Bartram & Cairncross, 2010; Fewtrell et al., 2005; Waddington et al., 2009).

Pit latrines

Pit latrines are the most basic and common excreta disposal facilities used in both rural and urban areas of developing countries. A recent systematic review estimated that approximately 1.77 billion people worldwide use pit latrines as their primary mode of sanitation (Graham & Polizzotto, 2013). Many households, particularly those in the developing countries, resort to pit latrines due to their low cost and maintenance (Cairncross et al., 2010; Tillett, 2013). Although pit latrines are very basic, those with slabs or platforms are considered to be "improved" pit latrines as it separates waste from the people that use the facilities and are a more hygienic alternative to open defecation and other unsanitary forms of waste disposal (WHO & UNICEF, 2015). There is a concern, however, that pit latrine effluent may infiltrate into the soils causing microbiological and chemical contamination of groundwater causing negative health impacts. The incidence of waterborne diseases is high in countries where pit latrine use is common, as they tend to have high rates of groundwater use for drinking water and this groundwater is often polluted (Tillett, 2013). In 2015, approximately 663 million people worldwide used water from unprotected wells and springs, which do not receive subsequent treatment, as their primary drinking water source (WHO & UNICEF, 2015). While natural processes, such as mechanical filtration by soil, may help reduce the concentration of microbial pathogens, microbes can travel through the soil and groundwater until they either reach a water well or are discharged into other bodies of water (Graham & Polizzotto, 2013).

Waterborne Viruses

The main pathogenic microbes responsible for water contamination can be grouped into bacteria, viruses, and protozoa. Coliform bacteria are used as the standard fecal indicator to analyze fecal contamination of water resources even though bacterial persistence is lower than that of viruses and protozoa (Blaschke et al., 2016; Rose & Gerba, 1991). Viruses are one and two orders of magnitude smaller than protozoa and bacteria, respectively, and are less likely to be filtered out. Due to their extremely small size (10 to 100 nm), they can infiltrate soils and travel up to 50m from pit latrines, which is approximately 25m more than the travel distance of both bacteria and inorganic pollutants (Graham & Polizzotto, 2013). The low rate of removal by inactivation and filtration is attributed to its small size and ability to survive without any nutrients in the subsurface (Pang, 2009; Yates et al., 1987).

Modelling viral transport

Studies on viral transport in the subsurface have been conducted by numerous researchers and the interactions that occur between microbes and soil particles are relatively well known (Jin & Flury, 2002; Powelson et al., 1995; Tim & Mostaghimi, 1991; Torkzaban et al., 2006; Yates et al., 1988). However, the processes that occur in pit latrines and the behavior fecal pathogens exhibit in these environments are not yet well understood (Feachem et al., 1983; Stenström, 2004). A theoretical framework has been developed to explain the processes regarding biodegradation of microorganisms in pit latrines (Nwaneri, 2009), and another study has quantified pit latrine hazard (Fleming, 2017), but virus reduction from pit latrines to groundwater is still lacking a method of quantification. This paper presents a preliminary model that simulates virus emissions from pit latrines to groundwater based on the available model inputs and parameters from a systematic literature review.

Objective and Research Questions

The objective of this study is to develop a model to assess viral emissions from pit latrines to groundwater and ultimately support groundwater risk management. The following research questions were formulated to further specify the research objective:

Research question 1: What are the processes influencing virus emissions in pit latrines and to what extent are they quantifiable?

Research question 2: What are the processes influencing virus emissions in the vadose zone and to what extent are they quantifiable?

Research question 3: How can the findings from research question 1 and 2 be used to extrapolate a model that quantifies viral emissions from pit latrines to groundwater?

A systematic literature review is conducted to present an overview of the available literature on virus modelling in pit latrines and the vadose zone, which is discussed in Chapter 2 and 3, respectively. Chapter 4 describes the development of a preliminary model based on the literature review for the transport and fate of viruses from pit latrines to groundwater. The model is applied to different scenarios based on the depth of pit latrines and the type of vadose zone media. Chapter 5 discusses the overall outcomes including the limitations of the model and areas of research that are further required to improve the model.

Chapter 2: Virus Transport in Pit Latrines

Introduction

This chapter describes the transport and fate of viruses in pit latrines. The processes occurring in pit latrines and the factors affecting the rate of virus movement and survivability in pits are discussed based on the literature review. Studies that have attempted to quantify these processes or developed a pit latrine model are also discussed.

Method

The literature review was conducted solely in Scopus, but other papers with original references were also incorporated in this study. The reviewed literature was selected using specific search terms with Boolean operators in Scopus. The search terms were based on the title of the article, abstract, and keywords (Table 2.1).

Table 2.1 Search terms used for the literature review in Chapter 2

Related to virus		**Related to pit latrines**		**Related to modelling**		**Related to fate and transport**
Virus OR Pathogens OR Microbes OR	AND	Pit latrine OR Sanitation OR Toilets	AND	Model OR Modelling	AND	Transport OR Pathway OR Movement OR Fate

Search Results

The search gave a total of 54 articles, of which 7 were considered relevant based on whether they contained information on processes related to pathogen fate in pit latrines. Other articles were identified using the option of related documents in both Scopus and Google Scholar, and through the reference lists of the reviewed articles. Expert interviews also provided more key publications and articles.

Results and Discussion

As apparent in the number of search results of the literature review, virus activity in pit latrines have not been extensively studied, and there are even less studies that look into virus emission modelling in pit latrines. Most of the relevant studies that resulted from the search were about quantitative microbial risk assessment (QMRA) or the development of a modified version of a QMRA, to assess the infection risk from drinking water systems or different types of sanitation methods. Other literature that analyzed pathogens from pit latrine effluents were all conducted as field experiments where samples were collected from different locations around pit latrines or nearby wells (Banerjee, 2011; Martínez-Santos et al., 2017; Wright et al., 2013). There are studies that document the filling rate of pit latrines, but there were limited studies on processes related to virus transport in pit latrines.

Processes affecting virus fate in pit latrines

The processes occurring in pit latrines can be categorized into physical and biological processes (Figure 2.1). Physical processes refer to the filling rate of the pit and the transfer of water and other soluble pit contents, whereas biological processes relate to the biological conversion of organic matter and the degradation of biodegradable matter and inactivation of viruses. Both processes are key factors in determining the extent of virus removal in pit latrines and the surrounding soil.

The contents of pit latrines may theoretically build up into four different layers over time as shown in Figure 2.1 (Nwaneri, 2009). The uppermost layer consists of the most recent addition of fecal matter that is readily biodegradable and the organic matter in the sewage sludge is subject to rapid aerobic degradation. The rate of biodegradation persists until the materials are no longer degradable or the next filling event that creates a new upper layer. The second layer also undergoes aerobic biodegradation but at a limited rate due to lower levels of oxygen. As fecal matter accumulates in the pit latrine, the organic matter buried deeper becomes devoid of oxygen and anaerobic biological processes begin to dominate. At this point, a large proportion of the sludge has undergone biological transformation and the rate of reaction is slowed with less virus removal than in the above layers. By the time the sludge reaches the bottom layer, the materials have stabilized and are non-biodegradable. There is negligible virus removal in this zone (Orner et al., 2018).

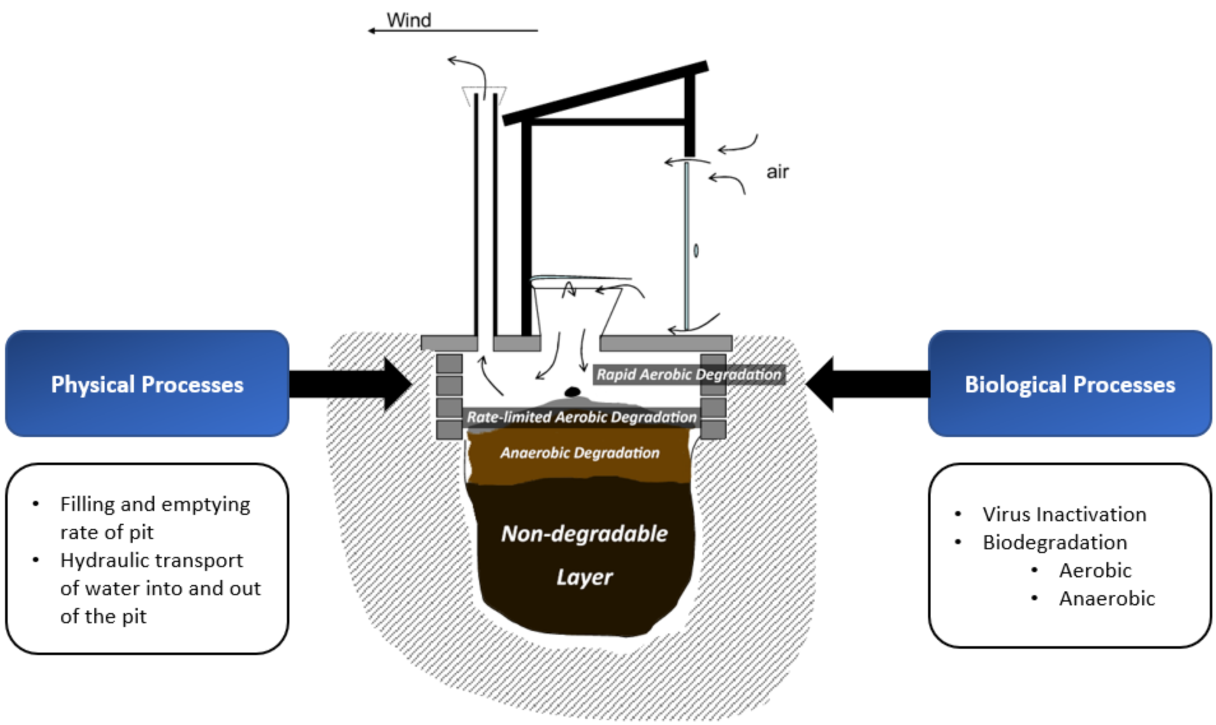

Figure 2.1 Diagram of the processes occurring in pit latrines and its different theoretical layers

The filling and emptying rate of pit latrines, and the content of material added to the pit determines the formation of the different layers. Biodegradation of organic matter lowers the rate of pit filling and the addition of non-degradable material increases the filling rate. There is increased virus inactivation in the presence of aerobic microorganisms (Hurst et al., 1980) therefore virus removal is higher when pit latrines are emptied more frequently. Pit latrines that are rarely or never emptied have a thick non-degradable layer that limits virus removal.

Virus inactivation in pit latrines is affected by various environmental factors including oxygen availability, temperature, moisture content, and residency time. Viruses compete with other fecal pathogens and can be inactivated through competition. It is estimated that 90% of pathogens from human feces are anaerobic, thus most have a higher chance of surviving in lower oxygen-deprived layers of pit latrines. Inactivation is further increased by high temperature and low moisture content. Desiccation in pit latrines was found to be a crucial factor in reducing virus concentrations in pit effluent (Magri et al., 2013). Temperature has a lesser impact in survival as the temperature of pit contents remain relatively stable. One study found that the temperature of the pit contents only decreased by 2°C over a depth of 1.5m (Nabateesa et al., 2017). The residency time of which the contents remain in the pit is regarded as the most important factor in reducing virus concentrations. Longer storage time of pit contents increases the reaction time for virus inactivation.

Models

The literature review revealed that studies on pit latrine modelling are limited. There are a few studies that have modelled the filling rate of pit latrines, but only one study has created a model on pathogen hazards and decay in pit latrines (Fleming, 2017). Besides this recent study, there are no models that describe the processes relating to virus removal in pit latrines which have been developed. The first component of pit latrine modelling is the virus load that is added into the pit (Fleming, 2017).

The initial loading rate of virus and can be expressed as

$$C_0 = \mathrm{Pr} \cdot \mathrm{S} \cdot \mathrm{E} \cdot \mathrm{P} \tag{2.1}$$

Where:

C_0 is the initial loading rate of virus;
Pr is the prevalence of virus infection;
S is virus shedding;
E is the average excreta rate per day per person;
P is population.

The prevalence of virus infection refers to the proportion of the population that is infected by the virus, and virus shedding is the amount of virus that is shed per gram of feces by an infected individual. This model assumes a steady-state virus loading rate and can be used to determine the loading rate of large communities. The next component of pit latrine modelling describes the virus load that is inactivated in the pit, which can be used to calculate the surviving load of virus that is subsequently leached into the soil.

$$C_t = C_0 e^{-Kt} \tag{2.2}$$

Where:

C_t is surviving load of virus in the pit at time t;
C_0 is the initial loading rate of virus;
K_t is the inactivation rate of virus at time t.

A relatively simple first order exponential decay equation is used to describe virus inactivation in this model. The survival of viruses is determined by their inactivation rate, the initial load that is introduced in the pit latrine, and the time it is given to settle in the pit. The environmental conditions in the pit, including temperature, moisture content, and pH, which have varying effects on viruses depending on their type, are incorporated in the inactivation rate.

Discussion and Conclusion

The literature review conducted in this chapter gives a good overview of virus survivability in pit latrines and the methods that can be used to quantify the virus load from the point of entry to decay in the pit over time. The literature search in SCOPUS resulted in limited articles, thus other publications recommended by expert individuals were also incorporated in this study.

The processes occurring in pit latrines and the association between viruses and the surrounding pit environment have not been extensively studied. The conceptual theory of processes occurring within the pit and the theoretical layers formed by the pit contents were developed based on field study experiments where fecal matter from a range of pit latrines were analyzed. Pathogen decay using a first order exponential decay equation was the only numerical model available that was used to calculate the change in virus load in pit latrines over time (Fleming, 2017). However, first order exponential decay models may not be the best representation for the complex nature of pit latrines. Given the lack of knowledge on pit latrines it may be premature to develop a complex model and thus the first important step would be to acquire a better understanding of the interaction between viruses and fecal matter as well as pit dynamics, including the accumulation and flow rate in pit latrines. The development of a model to accurately predict virus loads in pit latrines will be a complex procedure requiring extensive data. The insufficient scientific knowledge behind the interaction between viruses and pit latrines is further complicated by the sophisticated nature of pit latrines as the type, contents and dynamics are also determined by societal, cultural, and religious practices, which vary by region (Nawab et al., 2006). The requirements to develop an accurate model is further discussed in Chapter 5.

In the case of unlined pit latrines, the surviving viruses that reach the bottom of the pit latrine are able to infiltrate further into the vadose zone and the interactions they form with the soils are discussed in the next chapter.

Chapter 3: Virus Transport in the Vadose Zone

Introduction

This chapter describes the transport and fate of viruses in the unsaturated zone after they are leached from pit latrines. First, the processes and factors that control virus transport and fate are discussed. Second, models that have been used to quantify these processes are reviewed. In the last section, a brief review of existing models for virus transport in the vadose zone are presented. The processes and models presented in this chapter are based on the literature review.

Method

The literature review was conducted solely in Scopus, but information relating to model inputs and parameters on viral modelling in the vadose zone was also gathered using other online databases, including Google Scholar and Web of Science. The reviewed literature was selected using specific search terms with Boolean operators in Scopus. As shown in Table X, the search terms were based on the title of the article, abstract, and keywords.

Table 3.1 Search terms used for the literature review in Chapter 3

Related to virus		**Related to the vadose zone**		**Related to modelling**		**Related to fate and transport**
Virus OR Pathogens OR Microbes OR Biocolloids	AND	Vadose zone OR Unsaturated zone OR Soil	AND	Model OR Modelling	AND	Transport OR Pathway OR Movement OR Fate

Search Results

The search gave a total of 66 articles, of which 28 were considered relevant based on whether they contained information on processes, including sorption or inactivation of viruses, or numerical modelling of viruses in the vadose zone. Some of the articles were narrowed down based on their abstract, but in most cases, the articles had to be read to identify cases where the pathogen in study were viruses or that included model inputs and parameters on vadose zone viral modelling. Other articles were identified using the option of related documents in both Scopus and Google Scholar, and through the reference lists of the reviewed articles.

Results and Discussion

Processes affecting virus transport

Once the virus infiltrates into the vadose zone, there are two main processes that controls its fate: adsorption and inactivation of viruses. These are two of the most important mechanisms that controls virus transport in the subsurface (Jin et al., 2000; Yates et al., 1987). Both processes, which determine the persistence and extent of migration of viruses through the soil, are dependent on a variety of factors (Table 3.2).

In general, both the sorption and inactivation of viruses are determined by a three-fold interaction between the virus characteristics, the nature of the soil medium, and the climate of the soil atmosphere (Yates et al., 1988). Different virus species vary in size and have distinct chemical compositions that affect how they interact with their surroundings. The interaction is also determined by the soil properties, including pH, the texture of the soil, and the amount of moisture and organic matter present in the soil. These factors all influence how long viruses can persist and move through the subsurface. The soil environment is regulated by temperature and rainfall, which are important climatic factors that determine viral transport. The survival of viruses is favored by low temperatures, and higher rates of rainfall increases the mobility of adsorbed viruses through the vadose zone. The effect of these factors on virus sorption and inactivation are further discussed in the next section.

Table 3.2 Factors influencing virus fate in the vadose zone (adapted from Jin and Flury (2002))

Factor	**Influence on inactivation**	**Influence on sorption**
Virus type	Different virus types vary in their susceptibility to inactivation by physical, chemical, and biological factors.	Virus sorption to soils is related to physiochemical differences in capsid surface structure and amino acid sequence.
Temperature	Virus persistence is longer at low temperatures due to lower inactivation rates.	Virus movement is lower when inactivation rates are low and at higher temperature as adsorption to soils tend to increase.
pH	Most viruses are stable over a pH range of 3-9; however, survival may be prolonged at near-neutral pH values.	Generally, low pH increases virus sorption to soils; high pH causes desorption thereby facilitating greater mobility.
Moisture content	Most viruses survive longer in moist soils and even longer under saturated conditions; unsaturated soil may inactivate viruses at the air-water interface.	Virus movement increases under saturated flow conditions as compared to unsaturated conditions; the air-water interface can sorb viruses.
Ion type and concentration	Certain cations may prolong survival depending upon the type of virus.	Increasing ionic strength of the surrounding medium will generally increase adsorption to soils thus decrease mobility.
Organic matter	Organic matter may prolong survival by competitively binding to air-water interfaces where inactivation can occur; organic matter may also retard viral infectivity.	Soluble organic matter competes with viruses for adsorption on soil particles which may result in increased virus migration; bonded organic matter may provide hydrophobic binding sites for viruses which may decrease virus migration.

Microbial activity	Some viruses are inactivated in the presence of certain microbes; however, sorption to the surface of bacteria can be protective thus increase survival.	Unknown
Soil properties	Effects on survival are related to the degree of virus sorption, either prolonged or shortened depending on the properties of soil particles.	Greater movement in coarse-textured soils, while fine-textured soils, especially clays, tend to adsorb more viruses.
Virus association with soil	Survival is prolonged by adsorption to soil, although attachment to certain mineral surfaces (e.g. oxides and hydroxides) may cause inactivation.	Viruses interacting with soil particles are inhibited from moving through the soil matrix.
Hydraulic conditions	The air-water interface may inactivate hydrophobic viruses.	Virus movement generally increases at higher hydraulic loads and flow rates, reducing sorption.

Sorption

Sorption is one of the main mechanisms that reduces viral mobility and persistence in the subsurface. The ability for viruses to interact with soil particles is determined by its surface characteristics. Viruses and soil particles can adsorb onto one another primarily through electrostatic and hydrophobic interactions (Gerba, 1984; Schijven & Hassanizadeh, 2000; Sen, 2011). Viruses are typically negatively charged at most pH values in the subsurface and can adsorb more strongly in acidic soils (Corapcioglu & Haridas, 1984; Sen, 2011). The extent of sorption can change depending on the type of virus and soil properties, including pH, multivalent cations, and organic carbon content.

Viruses possess a protein capsid with a chemical composition that is unique to its species, which determines the electrical charge and hydrophobicity of its surface (Shields & Farrah, 1987). The isoelectric point (pI) of viruses, the pH at which the virus has a net charge of zero, has been used in past studies to estimate the variation of adsorption to charged surfaces (Gerba, 1984). Penrod et al. (1995) identified the isoelectric point of different species of viruses through microelectrophoresis and found that reovirus, vaccinia, and lambda phage have a more negative surface charge than bacteriophage MS2 at near-neutral pH. This indicates that viruses with a stronger negative surface charge increases the electrostatic repulsion thereby decreasing adsorption to soil particles. Furthermore, interactions may also differ not only by species but also by the virus strain (Gerba, 1984). Under the same environmental conditions, rotavirus and echovirus 1, 12, and 29 adsorbed to a lesser extent than 90% of the viruses that were tested, including other strains of echoviruses (Goyal & Gerba, 1979). Virus sorption is also influenced by hydrophobic interactions which have been found to differ between virus species. MS2 and echovirus 5 were found to be the most hydrophobic, while ϕX174 and echovirus 7 exhibited hydrophilic character (Schijven & Hassanizadeh, 2000). Hydrophobic viruses are more readily adsorbed to the solid-water and air-interface as they tend to avoid water molecules in the pores (Chu et al., 2001).

Soil properties are primarily shaped by the texture of the soil and the concentration of minerals that forms the vadose zone. Solids that have high isoelectric points are better at adsorbing viruses than those with low isoelectric points (Gerba, 1984). In general, granular sandy soils are weaker adsorbents than clay soils (Stevik et al., 2004). Clay soils have a relatively high cation exchange capacity (CEC) that enables it to hold various cations on its surface. The positively charged minerals enhance virus adsorption since viruses are usually negatively charged at natural groundwater pH. The surface of clay soils have a very heterogenous distribution of charges, thus viruses with different isoelectric points adsorb to different parts of the same clay particle (Gerba, 1984). Reoviruses were found to adsorb to the negatively charged section of the clay while T1 and T7 coliphages were bound to the positively charged end of the clay particle (Gerba, 1984).

Soil pH is an important factor influencing virus adsorption to soil particles as it determines the net surface charge and subsequently the ability to form electrostatic interactions. The extent to which pH influences adsorption depends on the type and strain of the virus. For Coxsackie B4, echo 1, ϕX174 and MS2, pH was an important factor affecting virus adsorption, whereas for polio 1, echo 7, coxsackie B3, and T2 and T4 bacteriophage, pH had no correlation with adsorption (Goyal & Gerba, 1979). Generally, viruses adsorb less at high pH because of the increased electrostatic repulsion between its surface and negatively charged soil particles (Azadpour-Keeley & Ward, 2005). Poliovirus had higher attachment rates to silica beads at lower pH, and in another column experiment a change in pH from 5.5. to 8.0 increased phage release suggesting an increase in pH was responsible for enhanced virus desorption (Bales et al., 1993).

The presence of multivalent cations and high ionic strength have been shown to increase virus adsorption in several studies (Gerba, 1984; Penrod et al., 1996; Redman et al., 1999). The thickness of the double layer around viruses and soil particles is affected by the ionic strength. An increase in ionic strength compresses the double layer and closes the distance between viruses and soil particles enhancing adsorption (Sen, 2011). Cations with higher valencies are more effective in promoting adsorption since soils are negatively charged. A study by Redman et al. (1999) showed that bacteriophage SJC3 was more strongly adsorbed to quartz when the ionic strength was increased by using multivalent cations such as Ca^{2+} or Mg^{2+} instead of Na^{+} that is a monovalent cation.

Organic matter in the form of humic substances, possess similar electrochemical characteristics as soils and therefore compete with viruses for the same adsorption sites (Stevik et al., 2004). Since dissolved organic matter is typically present in higher concentrations than viruses, they can significantly reduce the adsorption rate of viruses. Humic substances carry a negative surface charge and have the highest affinity to nonionic hydrophobic organic compounds (Schijven & Hassanizadeh, 2000). Furthermore, dissolved organic matter can reverse virus adsorption by causing adsorbed viruses to desorb from soil particles (Schijven & Hassanizadeh, 2000). This is partly caused by the ability of dissolved organic matter to disrupt hydrophobic bonds between the virus and soil. At the same time; however, organic matter can provide hydrophobic binding sites for viruses thus increasing the adsorption rate. Virus adsorption through hydrophobic bonding with organic matter will be greatest in soils with a strong negative surface charge (Schijven & Hassanizadeh, 2000).

Models

Virus adsorption can be expressed using different models and categorized into equilibrium and nonequilibrium kinetic models.

Virus adsorption is usually carried out in batch experiments under equilibrium conditions. Therefore, the kinetic behavior of viruses, which only occur before steady state, are not considered in equilibrium isotherms. (Schijven & Hassanizadeh, 2000). Equilibrium models assume a dynamic process where viruses perpetually adsorb and desorb against soil particles. The total adsorption rate is therefore dependent on the difference in the rate of adsorption and desorption (Jin & Flury, 2002). Equilibrium is reached when the rate of adsorption is equal to the rate of desorption. The most common nonlinear equilibrium and linear equilibrium models used to analyze virus sorption are the Langmuir and linear form of Freundlich isotherm, respectively (Gerba, 1984). The Langmuir isotherm assumes that all the sites for adsorption are of equal strength, that there is no interaction amongst adsorbed molecules, and that maximum adsorption rate corresponds to a saturated monolayer of viruses on the surface of soil particles (Schijven & Hassanizadeh, 2000).

The Langmuir isotherm is expressed as

Langmuir: $$S = \frac{S_{max} K_L C}{1 + K_L C} \quad (3.1)$$

Where:

S is the concentration of adsorbed viruses in the soil at equilibrium;
C is the concentration of free viruses in the soil at equilibrium;
S_{max} is the maximum adsorbed concentration when all the active surface sites are occupied;
K_L is the equilibrium constant related to the bonding energy.

The maximum adsorbed concentration S_{max} is therefore reached when the concentration of viruses is large ($C >> 1$). At low virus concentrations ($C << 1$); however, the Langmuir isotherm can be reduced to a linear isotherm. The linear form of the Freundlich isotherm is expressed as

Freundlich (linear form): $$S = K_d C \quad (3.2)$$

Where:

S is the concentration of adsorbed viruses in the soil at equilibrium;
K_d is the sorption coefficient;
C is the concentration of free viruses in the soil at equilibrium.

K_L and K_d are the sorption mechanisms that reflect the electrostatic interactions between viruses and adsorption sites in the soil. These mechanisms are defined by the experimental conditions and thus K_f and K_d values differ among studies. For example, in the study by Schwarzenbach et al. (1993), K_d was defined as

$$K_d = \frac{S_{om} f_{om} + S_{min} A + S_{ie} \sigma_{ie} A + S_{rxn} \sigma_{rxn} A}{C} \quad (3.3)$$

Where:

K_d is the sorption coefficient;
C is the concentration of free viruses in the soil at equilibrium;
S_{om} is the adsorbed concentration with organic matter;
S_{min} is the adsorbed concentration with minerals;
S_{ie} is the adsorbed concentration associated with electrostatic forces;
S_{rxn} is the adsorbed concentration associated with reversible chemical reactions;
f_{om} is fraction of organic matter;

A is the surface area of minerals;
σ_{ie} is the concentration of charged sites on the solid surface;
σ_{rxn} is the concentration of reactive sites on the solid surface.

The K_d values reported from different studies have been compiled by Jin and Flury (2002), which shows how much K_d can vary depending on experimental conditions (Table 3.3). The Freundlich isotherm is suitable when the adsorption data conforms to a linear relationship. It also shows that the adsorption of viruses can be a reversible process (Matthess & Pekdeger, 1981). This is indicated by a large number of active sites and when equilibrium strongly favors the suspended phase over the adsorbed phase (Schijven & Hassanizadeh, 2000). One of the limitations of the Freundlich isotherm is that it neglects the maximum quantity of adsorption whereas the Langmuir model accounts for a saturation limit for adsorption (Coppola et al., 2014).

Table 3.3 Sorption coefficients K_d of different experiments

Virus	**Sorbent**	**pH**	**Equilibrium time and temperature**	**K_d (mL g^{-1})**	**References**
MS-2	Hydrophilic silica	5	60 min, 24°c	580	(Bales et al., 1991)
	Hydrophilic silica	5	60 min, 4°c	270	
	Hydrophilic silica	7	60 min, 4°c	0	
	Hydrophilic silica	5	60 min, 4°c	6.6	
	Hydrophilic silica	5 and 7	60 min, 4°c	8300	
ϕX174	Ottawa sand	7.5	3h, 6-9°c	0.74	(Jin et al., 1997)
MS-2	Ottawa sand	7.5	3h, 6-9°c	0	
MS-2	Ottawa sand	7.5	3h, 6-9°c	0	(Thompson et al., 1998)
MS-2	Loamy sand	7.5	3h, 6-9°c	0.076	
MS-2	Sandy loam	7.5	3h, 6-9°c	0.44	
ϕX174	Ottawa sand	7.5	3h, 6-9°c	0.44	
ϕX174	Sandy loam	7.5	3h, 6-9°c	6.5	

In addition to equilibrium sorption, nonequilibrium models include the kinetic behavior before equilibrium is reached (Schijven & Hassanizadeh, 2000). Nonequilibrium models are based on first-order sorption kinetics and has a two-phase process (Yates et al., 1988). In the first process, the viruses are transported near the soil particles. In the second process, viruses adsorb onto the soil particle through electrostatic and hydrophobic interactions. The kinetics of the system takes into account the virus sorption rate to the soil, the virus desorption rate, and the inactivation of suspended and adsorbed viruses (Schijven & Hassanizadeh, 2000). Nonequilibrium models assume that viruses can inactivate while suspended in solution, adsorb reversibly and irreversibly to soil particles, inactivate after adsorption, and reversible sorption can become irreversible (Jin & Flury, 2002).

Inactivation

The infectivity of viruses and transportation to groundwater is significantly reduced by the process of inactivation. Inactivation occurs when the protein structure is disrupted and there is degradation of the viral nucleic acid (Jin & Flury, 2002). The rate of inactivation is affected by a variety of factors. Temperature is the most influential factor that correlates to the inactivation of viruses (John & Rose, 2005). The rate of inactivation is directly proportional to an increase in temperature (Gerba & Choi, 2006). A regression analysis conducted by Schijven and Hassanizadeh (2000) showed that the rate of inactivation depends on the type of virus as they have varying sensitivity towards temperature change. For example, the rate of inactivation of MS2 and echovirus 1 were found to be more sensitive to temperature than poliovirus 1.

The moisture content of the soil and the rate of virus adsorption to solids were also found to be important factors influencing virus inactivation. Viruses typically persist longer in moist environments compared to dry conditions (Bagdasaryan, 1964; Gerba & Choi, 2006). Although this is the general trend, the survival of viruses depends on the level of moisture relative to the optimal moisture content. When the moisture content of a sandy soil was increased from 5 to 15% there was an increase in the inactivation rate of poliovirus; however, when the moisture content was further increased from 15 to 25%, inactivation decreased (Hurst et al., 1980).

Virus interactions with solids generally reduce virus inactivation. The stronger the attachment of viruses to soil particles, the lower the inactivation rate. Viruses are therefore better protected in strongly adsorbed clay soils compared to sandy soils (Parsai et al., 2018). When viruses were tested in five different types of soil including clay, clay loam, loamy sands, sand, and organic muck, the virus survival rate was the highest in the clay soils, where it took 8 weeks for 99% of the virus to inactivate (Sobsey et al., 1986). The increase in survival rate of viruses while adsorbed to solid particles has been associated with protection from enzymes and enhanced stability of the viral capsid (Gerba, 1984). However, viruses were found to be susceptible to inactivation when they associated with certain cations and metal oxides. MS-2 and f2 were inactivated when they came in contact with aluminum, zinc, and magnesium ions (Yamamoto et al., 1964). Adsorption of viruses to metal oxides, including manganese dioxide and lead oxide were also responsible for inactivation. Adsorption to iron oxides inactivated MS-2 but had no effect on ϕX174, indicating that inactivation caused by adsorption to metal oxides depends on the virus species (Jin & Flury, 2002; Yamamoto et al., 1964).

The presence of other microorganisms may enhance the inactivation of viruses. Anaerobic microorganisms did not significantly affect virus inactivation, but aerobic microorganisms decreased the survival rate of poliovirus 1 (Schijven & Hassanizadeh, 2000). Since most experiments used dissolved oxygen concentration to determine the aerobic and anaerobic condition of the experiment, it is unclear if the inactivation of viruses was directly affected by the oxygen concentration or by the presence of microorganisms resulting from the oxygen concentration. Some studies reported no significant differences in the inactivation rate of viruses. The study by Matthess et al. (1988) showed that there was no significant difference in the inactivation rate of coxsackievirus A9 and B1, and echovirus 7 in both aerobic and anaerobic conditions.

Models

The inactivation of viruses is a time-dependent process that can be modelled as a first-order reaction. A linear inactivation model can be expressed as

$$\frac{dC}{dt} = KC \tag{3.4}$$

Where:

C is the concentration of viruses at time t;
K is the first-order inactivation constant ($time^{-1}$).

In this equation, K is the sum of all the independent variables affecting virus inactivation, and will depend on the factors that are included in a study. In one study, temperature, pH, moisture, and the method of waste application were considered the most important factors influencing inactivation (Reddy et al., 1981). The functional relationship of these four factors were identified and integrated as the inactivation constant, expressing K as

$$t_{1/2} = \frac{0.693}{K_2} \qquad K_2 = K_1 \times F_T \times F_M \times F_{pH} \times F_{ma} \tag{3.5}$$

Where:

K_2 is the inactivation constant measured at moisture content of m_1 day^{-1};
K_1 is the inactivation constant adjusted to the desired moisture content of m_2 day^{-1};
F_T is the coefficient for temperature;
F_M is the coefficient for soil moisture content;
F_{pH} is the coefficient for soil pH;
F_{ma} is the coefficient for method of application.

In another study, a regression analysis was conducted, and the authors found that 77.5% of the variation in the rate of virus inactivation was a result of temperature, indicating that temperature is the most significant factor affecting inactivation (Yates et al., 1988). The equation for the rate of inactivation of viruses as a function of temperature has been used to develop the VIRTUS model and is expressed as

$$\mu = -0.181 + 0.0214 \times \mathrm{T} \tag{3.6}$$

Where:

μ is the inactivation rate of viruses ($\log_{10}$ day^{-1});
T is temperature.

When viruses are seen as aggregates or there is variation in how the factors affect different viruses, the exponential decay model is used to determine the rate of virus inactivation (Azadpour-Keeley & Ward, 2005; Coffey et al., 2010; Matthess & Pekdeger, 1981; Tim & Mostaghimi, 1991; Yates et al., 1988). The half-life ($t_{1/2}$) can be calculated from the inactivation rate. The equation is expressed as

$$C_t = C_0 e^{-K_t} \tag{3.7}$$

Where:

C_t is the concentration of virus at time t;
C_0 is the initial concentration of virus;
K is the inactivation constant.

Existing models on virus transport

Like any model, virus transport in the subsurface is characterized by the conceptual framework of the model. Differences occur due to the availability and quality of data, and because the processes and parameters considered in models vary among authors. Simplified models that only require a few parameters require less data, but are limited in application, whereas complex models that reveal more about virus transport often require more input information and are thus limited to laboratory settings as not all the information can be obtained in field experiments (Azadpour-Keeley & Ward, 2005). Most of the models on microbial transport in the subsurface focus on groundwater and aquifers even though many studies have shown that the unsaturated zone has a greater effect on virus removal than the saturated zone (Nimmo, 2009).

There are several models that have been specifically developed for virus transport in the vadose zone, while some groundwater models have incorporated the unsaturated zone module in their updated versions. All the models are based on the advection-dispersion equation, which is combined with other reaction processes including sorption and inactivation (Jin & Flury, 2002). The earlier virus transport models assumed sorption to be linear and at equilibrium, but recent models have included the concept of kinetics to incorporate processes such as virus deposition, and account for surface chemistry of binding site, and other complex soil mechanisms (Azadpour-Keeley & Ward, 2005). The available mathematical models that can be used or have been specifically developed to model virus transport in the vadose zone are summarized in Table 3.4 (Azadpour-Keeley & Ward, 2005).

Table 3.4 Available models for virus transport in the vadose zone

Model	**Description**	**Processes considered**	**References**
MODFLOW-UZF (2005)	The vadose module for MODFLOW replaces saturated properties with unsaturated parameters which can be used to model water flow or virus transport.	Advection, dispersion, degradation, volatilization, and sorption.	Blum et al. (2001), Niswonger and Prudic (2005)
VIRULO (2002)	A Monte Carlo-based screening model for predicting fate and transport of viruses in the unsaturated zone.	Advection, dispersion, sorption, inactivation, and uncertainty.	Faulkner et al. (2003)
Model by Chu et al. (2001)	1D model for virus transport in the subsurface based on a three-phase system.	Advection, dispersion, adsorption, mass transfer, and inactivation.	Chu et al. (2001)
Model by Sim and Chrysikopoulos (2000)	1D virus transport model in homogeneous, unsaturated porous media.	Advection, dispersion, adsorption, inactivation, and mass transfer.	Sim and Chrysikopoulos (2000)
HYDRUS-1D (1998) and -2D (1999)	A model for simulating the movement of water, heat, and multiple solutes in variably saturated media.	Advection, dispersion, sink term, conduction, convection, sorption, degradation, inactivation, and uncertainty.	Simunek et al. (2005)
VIRTUS (1991)	A model for transport and fate of viruses in the vadose zone. The virus transport is coupled with the flow of water and heat through soil.	Advection, dispersion, sorption, and inactivation.	Yates and Ouyang (1992)

Discussion and Conclusion

An overview of the processes and models on virus transport and fate were provided based on the literature review. The literature search was carried out using SCOPUS with specific search terms, limiting the search to its database and creating the possibility of missing other literature that may have been relevant to this study. These risks were mitigated by referring to original references and considering other publications recommended by expert individuals.

Processes influencing virus transport and fate such as adsorption and inactivation and the factors affecting them have been extensively researched and are relatively well known. The chemistry of the soil including pH, ionic strength, organic matter content, moisture content, temperature, cations, and virus properties such as surface characteristics and isoelectric point have found to affect the rate of sorption and inactivation of viruses in the vadose zone. Although these relationships are well known, some of the factors have been difficult to quantify and are therefore not all addressed in models (Yates et al., 1988). For example, the inactivation rate used in the VIRTUS model only incorporates temperature as the only factor that affects inactivation. The necessity for the simplification in models can be explained by the complex nature of soil properties. Temperature is one of the factors that has a clear relationship on the inactivation of viruses, whereas the effect of pH on adsorption can vary by either promoting adsorption or desorption due to the heterogenous nature of the soil. Similarly, organic matter can reduce adsorption of viruses as they compete for the same binding sites; however, at the same time the surface of organic matter may provide hydrophobic binding sites for viruses thereby increasing adsorption. Such factors make it more difficult to incorporate them into models and are responsible for greater uncertainty in modelling virus transport in the vadose zone.

This overview shows the processes and factors related to virus transport and how they can be quantified for modelling. The models are greatly dependent on laboratory conditions and can vary from simple equilibrium models to more sophisticated kinetic models. The later models of virus transport in the vadose zone are more advanced and consider more processes but are more data intensive. Earlier models are based on equilibrium irreversible sorption, whereas later models include the concept of kinetics that account for reversible sorption and the complexity of the soil matrix. Based on the knowledge obtained from Chapter 2 and Chapter 3, a model on the transport and fate of viruses from pit latrines to groundwater is further discussed in the next chapter.

Chapter 4: Modelling Virus Emissions from Pit Latrines to the Vadose Zone

Introduction

This chapter relates to research question 3 and describes a preliminary model on the transport and fate of viruses from pit latrines to the lower boundary of the vadose zone. The model has been developed based on the literature review in Chapter 2 and 3 and will be applied to estimate the removal rate of viruses for different pit and soil conditions. The model deals with three main processes: (1) the initial virus load that enters the pit latrine, (2) virus reduction in the pit latrine, and (3) virus reduction in the vadose zone. The model focuses on virus reduction since most guidelines on water quality and setback distance—defined as the distance between latrines and a drinking water well—are based on log reduction of viruses, regardless of the virus load in the drinking water source (Azadpour-Keeley & Ward, 2005; Dunn et al., 2014). The model is summarized in Figure 4.1 and further discussed in the results section.

Method

The model is simulated using the inputs and parameters from the literature review. The model is applied to four case studies of Katanga, Bester's Camp, Kumasi, and Wajir, which are areas that widely use pit latrines as their main on-site sanitation system.

Due to the uncertainty of the parameters, a sensitivity analysis was conducted to examine the effect of variation of each parameter on the model output. The parameters that were included in the analysis are fecal flow or pore-water velocity (v), longitudinal dispersivity (α), and the removal rate (λ) of viruses, which are the main components of the model influencing virus reduction. A range from half of the initial value up to double of the value were tested in the sensitivity analysis. The results are shown for pit latrines at a depth of 3m.

Results

The pit latrine-vadose zone model is comprised of three components (Figure 4.1). The first component is the virus loading rate which represents the number of viruses for a given species that is introduced into the pit daily. The second component describes the fraction of removed viruses in the pit latrine at different depths. The surviving viruses that infiltrate into the vadose zone are subject to further removal, which is determined by the last component of the model. As a preliminary model the following assumptions were made:

- Steady state input: the loading rate for each virus type is constant. The amount of virus introduced daily into the pit is fixed.
- Virus load decreases linearly with depth; therefore, virus removal kinetics are explained using a linear relationship.
- Pit latrine characteristics: unlined, and only contain fecal matter.
- The pit latrine content and the vadose zone are homogenous.
- The fecal matter in pit latrines exhibit similar characteristics and undergo similar interactions to the soils of the vadose zone.

- No horizontal leakage and overflow of pit latrines: the virus reduction is only affected by removal and inactivation rates, pore water velocity, dispersivity, and the depth of pit latrine/vadose zone.
- Only vertical water movement and longitudinal dispersion only occurs in the direction of the flow.
- The removal and inactivation rates are constant for all viruses of the same species. They only vary between different virus species.

As can be seen in the literature review in Chapter 3, the difference in the modelling approach arises from the combination of additional processes that are incorporated in the simulation. Exponential decay models for evaluating virus reduction in the subsurface has been widely used in studies and although they are easily applicable to many situations without requiring much data, they simplify or neglect important processes affecting virus reduction, including virus kinetics, and their interaction with the surrounding media. Other models on transport of viruses in the subsurface consider solute transport—which is governed by advection and dispersion—as its main component. The advection-dispersion equation has been used in many studies and is the base formula for the existing models (Table 3.4), and has been used for both simple linear and more complex non-linear systems (Corapcioglu & Haridas, 1984; Jin et al., 2000; Torkzaban et al., 2006; Yates et al., 1988; Zhang et al., 2012). In this study, the log reduction form of the 1D advection-dispersion equation was combined with the inactivation and removal rates found in literature to evaluate the total virus reduction in pit latrines and the vadose zone (Figure 4.1.).

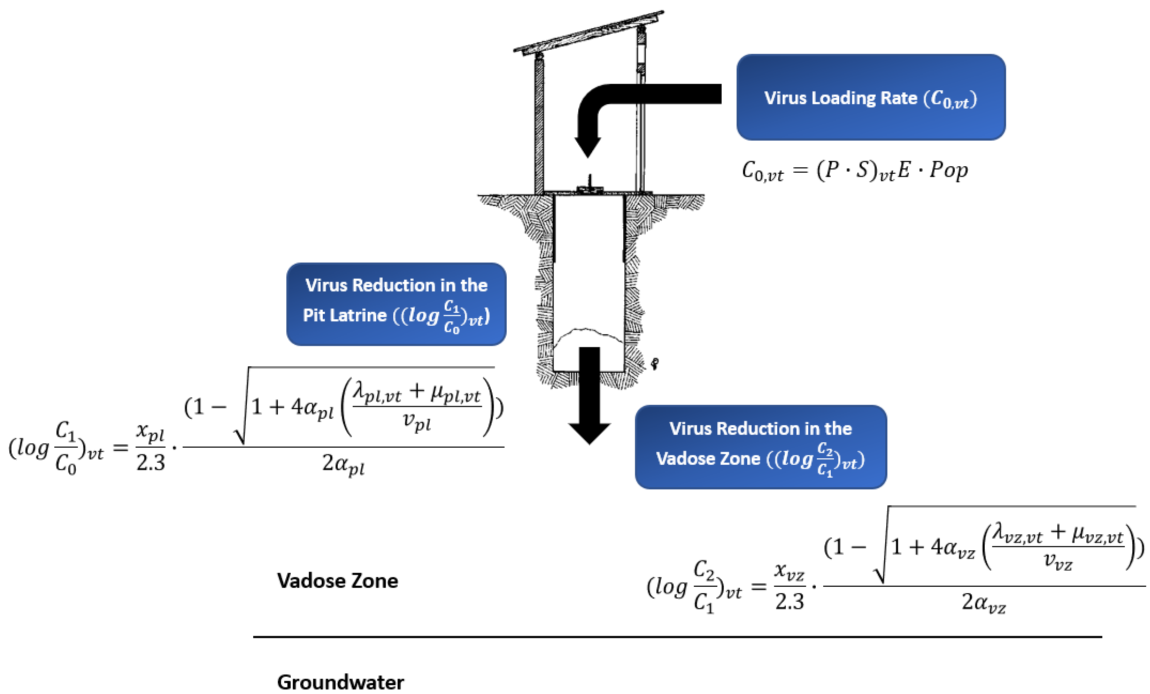

Figure 4.1 Conceptual framework of the pit latrine-vadose zone model

Where:

$C_{0,vt}$ = Loading rate of virus type vt
P_{vt} = Prevalence of virus type vt

S_{vt} = Shedding rate of virus type vt
E = Average excreta rate per day per person
Pop = Population
x_{pl} = Depth of pit latrine content
α = Longitudinal Dispersivity
λ_{vt} = Virus removal rate of virus type vt
μ_{vt} = Virus inactivation rate of virus type vt
v_{pl} = Fecal flow velocity in pit latrine
x_{vz} = Depth of vadose zone
v_{vz} = Pore water velocity in the vadose zone

(Subscript $_{pl}$ = pit latrine, $_{vz}$ = vadose zone)

Virus Loading Rate

The first step to the pit latrine-vadose zone model is to determine the virus input. The following equation was found suitable to express the virus load that is introduced in pit latrines (Fleming, 2017). The first component of the model, which represents the loading rate of a given virus species, is determined by the prevalence of virus infection or the proportion of infected people amongst a given population; virus shedding which is the amount of viruses that is excreted by an individual per gram of feces; the excreta rate or the amount of feces excreted by an individual in grams per day; and the total population.

$$C_0 = \mathrm{Pr} \cdot \mathrm{S} \cdot \mathrm{E} \cdot \mathrm{P} \qquad (4.1)$$

Where:

C_0 is the initial loading rate of virus;
Pr is the prevalence of virus infection;
S is virus shedding;
E is the average excreta rate per day per person;
P is population.

The amount of feces generated by a community depends on their diet type and level of income (Rose et al., 2015) (Table 4.1). Fiber intake is considered one of the many factors causing the variation in excreta rate. Vegans have the highest fiber intake and have an average fecal mass of 225 grams per day, followed by vegetarians with an excreta rate in the range between 160-189 grams per day, while omnivores had the lowest at 118-153 grams per day. The level of income also has a significant effect on fecal mass. The excreta rate of low-income communities has an average of 250 grams per day whereas high income areas had a relatively lower excreta rate of 126 grams per day. The type and shedding rate of viruses in fecal matter was found to vary between developing and developed countries (Guardabassi et al., 2003). Although viruses are present in any water body around the world, enteric viruses such as Hepatitis A, rotavirus, and enteroviruses are likely to be higher in developing countries due to the lack of sanitation, and protection against diarrheal diseases (Clemente-Casares et al., 2003). The shedding rate for different viruses are shown in Table 4.2.

Table 4.1 Excreta Rates

Category	Excreta Rate (feces produced in gram per day)	References
High Income	51-796 (126)	Davies et al. (1986), Klugman (2011), Reddy et al. (1998)
Low Income	75-520 (225)	
Omnivore	118-153 (136)	
Vegetarians	160-189 (175)	
Vegans	(225)	

Table 4.2 Virus Shedding

Virus Type	Shedding (number of virus excreted per gram of feces)	References
Hepatitis A	$\sim 10^{10}$	Ansari et al. (1991), Bishop (1996), Bruisten et al. (2001), Coulepis et al. (1980), Gerba et al. (1996), Graham et al. (1994), Mao et al. (1980), Okhuysen et al. (1995), Yotsuyanagi et al. (1996)
Rotavirus	10^{10} - 10^{12}	
Norovirus	10^{4}-10^{6}	
Enterovirus	10^{8}-10^{10}	

Virus Reduction in the Pit Latrine

One of the key assumptions made for the pit latrine is that the contents of the pit behaves in the same way as the vadose zone media and therefore undergo interactions that are comparable to how soils interact with viruses in the subsurface. Considering this assumption, the 1D advection-dispersion equation coupled with first-order virus removal and inactivation rate was used to determine the log reduction of viruses in pit latrines.

$$(log\frac{C_1}{C_0})_{vt} = \frac{x_{pl}}{2.3} \cdot \frac{(1 - \sqrt{1 + 4\alpha_{pl}\left(\frac{\lambda_{pl,vt} + \mu_{pl,vt}}{v_{pl}}\right)})}{2\alpha_{pl}} \tag{4.2}$$

Where:

x_{pl} = Depth of pit latrine content
α_{pl} = Longitudinal dispersivity in pit latrine
$\lambda_{pl,vt}$ = Virus removal rate of virus type vt in the pit latrine
$\mu_{pl,vt}$ = Virus inactivation rate of virus type vt in the pit latrine
v_{pl} = Fecal flow velocity in pit latrine

The formula is for steady-state fecal flow conditions and was solved in the form of log reduction of C_1 relative to the initial load C_0 at a certain pit depth in the direction of fecal flow. The initial virus load was calculated using equation 4.1. The virus reduction in pits with different depth was simulated using equation 4.2 and the surviving virus load that reaches the bottom of the pit was used as the new initial virus load for calculating virus reduction in the vadose zone.

The pore water velocity was calculated using Darcy's Law. Given the steady-state and flow conditions, the hydraulic gradient or the change of water pressure over the depth of the pit content was given the value of 1. The fecal flow velocity was calculated as:

$$v = K \cdot \theta \tag{4.3}$$

Where:

v = fecal flow velocity / pore water velocity
K = hydraulic conductivity
θ = porosity

Due to the lack of data availability on the parameters for pit latrines, the values for a soil type that lies between clay and silty clay were chosen for the fecal matter that accumulates in the pit. It is estimated that 75% of feces are composed of water making them relatively wet and viscous (Rose et al., 2015). The remaining 25% is solid material with up to 93% of organic matter with high carbon content (Rose et al., 2015). Clay soils are much alike as they have a high water-holding capacity and are usually full of moisture. Water particles are tightly bound within the tiny pores between each clay particle. The organic content of clay soils is also comparable to that of fecal matter. Clay particles have a high humus content and can retain nutrients for a long period of time. Due to similar water content and viscosity, it can be assumed that temperature has a similar effect on feces; fecal matter clods in dry conditions and smears in wet conditions like clay soils do. The pH of fecal matter is also similar to that of clay soils. The feces of an average healthy person is slightly acidic at pH 6.6 (Osuka et al., 2012). Although the pH of clay soils vary depending on the geographical region and use of fertilizers in the area, they are generally acidic ranging from 5.5 to 6.5 (Dixon, 1991; Page, 1952). The parameter values for rotavirus in a default pit latrine set by the author is shown in Table 4.3.

Table 4.3 Parameters for the pit latrine component

Parameter	**Value**	**References**
K_{pl} (m/d)	0.21	Banerjee (2011), Batjes (2005), Domenico and Schwartz (1998), Jin and Flury (2002) Kébré et al. (2017), Philips and Castro (2003), Reynolds et al. (2002) Ružičić et al. (2013), Schijven and Hassanizadeh (2000), Sprenger et al. (2015)
θ_{pl}	0.45	
v_{pl} (m/d)	0.0945	
$\lambda_{pl} + \mu_{pl}$ (log/m)	0.13	
α_{pl} (m)	0.0025	

Virus Reduction in the Vadose Zone

The viruses that survive and reach the bottom of the pit latrine can infiltrate into the vadose zone where they are subject to further removal and inactivation. The 1D advection-dispersion equation coupled with virus removal and inactivation rates was used to calculate virus reduction in the vadose zone.

$$(log\frac{C_2}{C_1})_{vt} = \frac{x_{vz}}{2.3} \cdot \frac{(1 - \sqrt{1 + 4\alpha_{vz}\left(\frac{\lambda_{vz,vt} + \mu_{vz,vt}}{v_{vz}}\right)})}{2\alpha_{vz}} \quad (4.4)$$

Where:

x_{vz} = Depth of the vadose zone
α_{vz} = Longitudinal dispersivity in the vadose zone
$\lambda_{vz,vt}$ = Virus removal rate of virus type vt in the vadose zone
$\mu_{vz,vt}$ = Virus inactivation rate of virus type vt in the vadose zone
v_{vz} = pore water velocity in the vadose zone

Virus reduction in the vadose zone is determined by its composition. The model parameters for different soil types were collected from literature. Five soil types—excluding gravel—out of the twelve major textural classes defined by the USDA (Daddow & Warrington, 1983) were selected based on the available data from literature. The classification of the soil types used in this study are shown using a simplified triangle in Figure 4.2. Other parameters such as the pore water velocity was calculated using Darcy's Law, and the removal and inactivation rates of viruses in different vadose zone media were selected from the database by Pang (2009). A summary of the parameters used in the model application for different soil types is shown in Table 4.4.

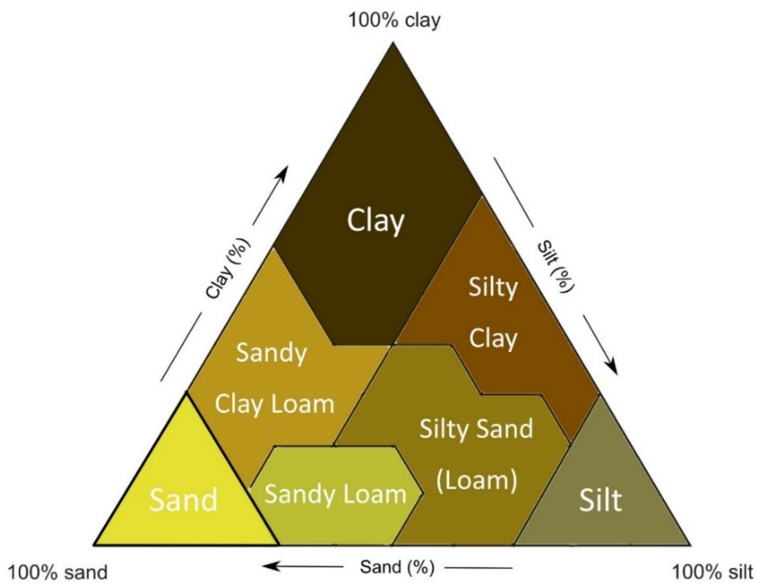

Figure 4.2 Soil Classification used in this study. Modified from Daddow and Warrington (1983).

Table 4.4 Vadose zone parameters for different soil type

Parameter / Soil Type	K_{vz} (m/d)	θ_{vz}	v_{vz} (m/d)	$\lambda_{vz} + \mu_{vz}$ (log/m)	α_{vz} (m)
Gravel	18	0.31	58.06	0.32	0.05
Sand	15.2	0.36	42.22	0.33	0.03

Silty sand (loam)	2.98	0.37	8.05	0.46	0.01
Sandy clay	0.55	0.26	2.12	0.68	0.008
Silty clay	0.24	0.44	0.55	0.88	0.004
Clay	0.11	0.49	0.22	0.97	0.001

Model Simulation

The model was applied to four case studies in Africa. The location of each case study was chosen based on the availability of data and characteristics of each area. The shedding rate or the rotavirus shed per gram of feces and excretion rate were kept the same for all the areas—10^{10} virus particles and 128 grams per day, respectively—and the percentage of infected people was determined by the respective countries' national rotavirus prevalence. Katanga and Bester's Camp are small districts within a city whereas Kumasi and Wajir are cities themselves, therefore only 33%, which is the fraction of people in urban areas that dwell in slums, was accounted for in the simulation (Dakpallah, 2011). The data used for the simulation is shown in Table 4.5 and the results of the rotavirus load that is introduced in pit latrines is shown in Figure 4.3.

Table 4.5 Rotavirus Prevalence and Population

Case Study	Prevalence	Population	References
Katanga	0.37	20000	Bwogi et al. (2016), Dakpallah (2011), John et al. (2014), Mwenda et al. (2010), Page (1952), Patel et al. (2013), http://www.hopeforlifekatanga.com/katanga/, http://informalcity.co.za/besters-camp-2
Bester's Camp	0.20	35000	
Kumasi	0.33	363000	
Wajir	0.40	218000	

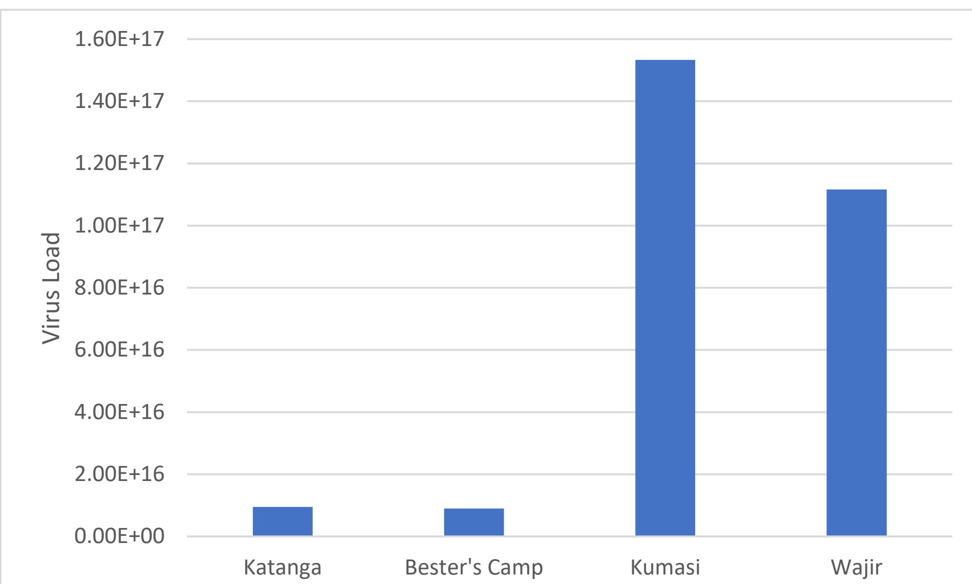

Figure 4.3 The loading rate of rotavirus

The rotavirus load that is introduced into pit latrines daily is the highest in Kumasi at 1.12 x 10^{17} particles and the lowest in Bester's Camp at 8.96 x 10^{15} particles. The parameters shown in Table 4.3 were used to simulate virus reduction in pit latrines (Figure 4.4).

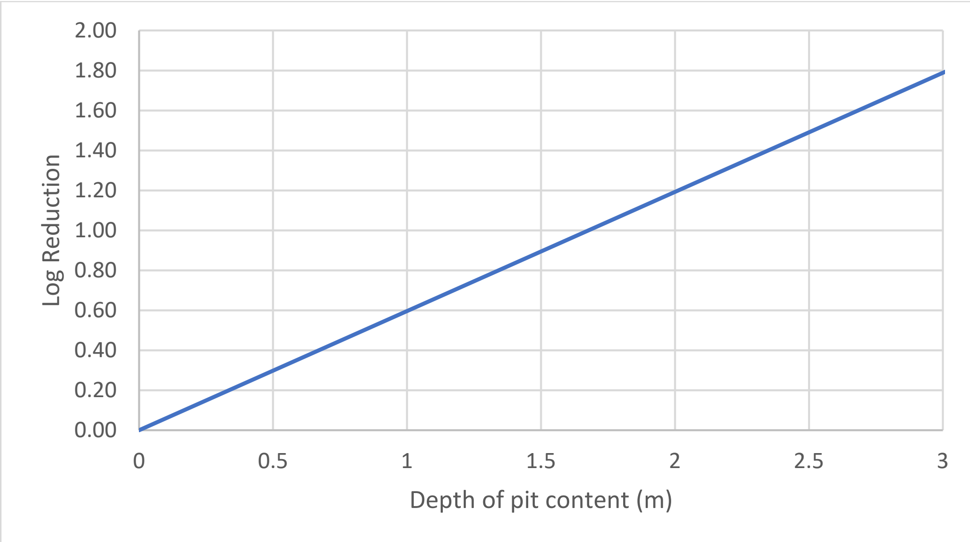

Figure 4.4 Virus Reduction in Pit Latrines

A pit latrine simulated in this study can reduce rotavirus concentrations by 1 log at a pit depth of 1.7m. For a 2 log reduction the pit has to be deeper than 3 meters. The amount of Rotavirus reduction in six different types of vadose zone media were compared (Figure 4.5).

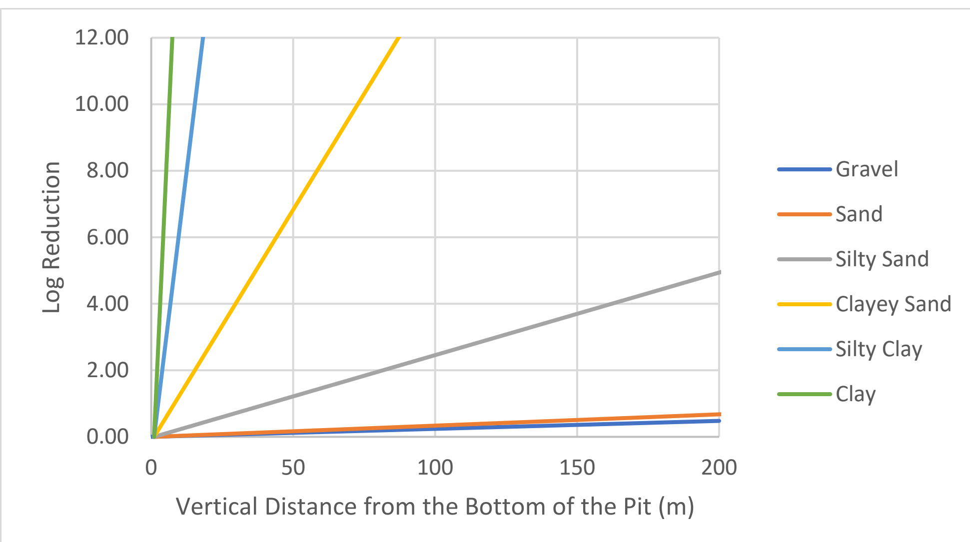

Figure 4.5 Virus Reduction by different vadose media

The log reduction of viruses vary greatly depending on the soil properties of the vadose zone. Gravel and sand have low rates of virus reduction and can only reach 0.48 and 0.68 log reduction, respectively, even after it has infiltrated the vadose zone to a depth of 200m. At a vadose zone depth of 50m, silty sands and clayey sands can reduce viruses up to 2.3 log and 7 log, respectively. Clay soils were found to be the most efficient at reducing virus concentrations in the subsurface. At a mere depth of 2m, clay soils can already reduce virus concentrations by 4 log, and at 5m more than 9 log reduction.

The information relevant to the case studies is summarized in Table 4.6. Using the data obtained from literature the model was applied to the four case studies. Due to the lack of data for these regions specifically, the national average depth of pit latrines and soil type for their respective countries were used. The results are shown in Figure 4.6.

Table 4.6 Summary of the case studies

Area	**Average Pit Depth (m)**	**Soil Type**	**Vadose Zone Depth**	**References**
Katanga	3	Sandy clay	15	Barrett et al. (1999), Dennis and Dennis (2012), Fey (2010), Mara (1984), Minai (2015), Omulo et al. (2017), Oord et al. (2014), Seal et al. (2018), Sedoawu (2015), Tetteh et al. (2016)
Bester's Camp	1	Sandy loam	40	
Kumasi	2	Sandy clay	27	
Wajir	3	Sandy clay	130	

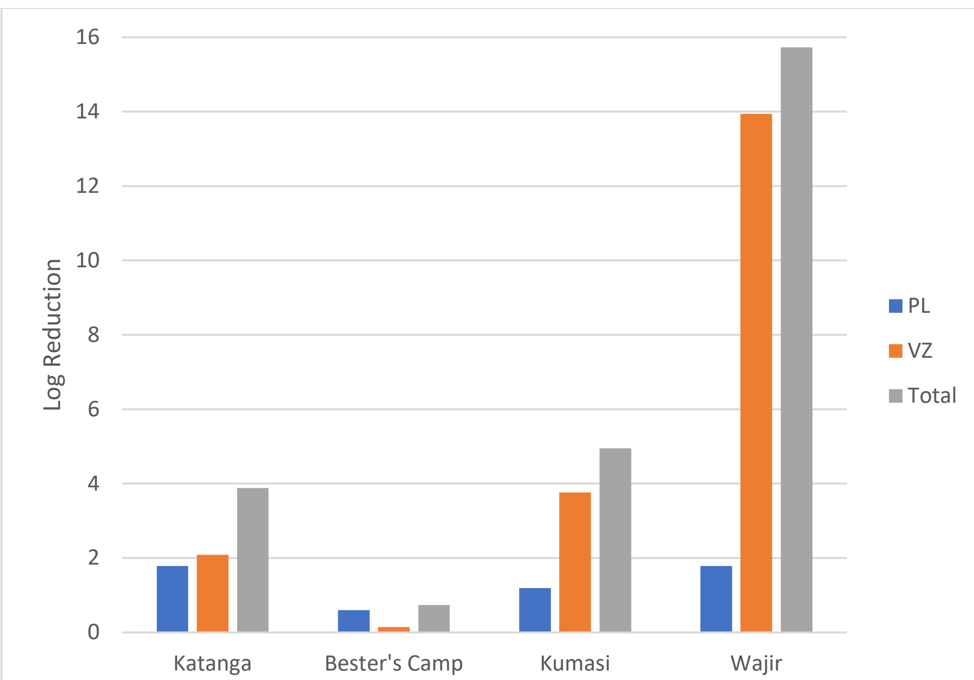

Figure 4.6 Virus reduction in pit latrines and the vadose zone

In most cases, virus reduction in the vadose zone is greater than in pit latrines. The only exception is Bester's Camp where there is 0.6 log reduction by pits but only 0.14 log reduction by the soils beneath them. There is less than 1 log reduction before viruses infiltrate into the groundwater. The virus reduction in pits and the vadose zone is similar in Katanga, whereas in Kumasi and Wajir the vadose zone has a greater impact in the total amount of virus reduction. In Wajir the vadose zone can reduce the virus load up to 14 log, which is nearly 8 times the reduction that can occur in pit latrines.

The total log reduction was applied to the initial load of rotavirus and the final virus load that reaches the groundwater in each area was calculated (Figure 4.7).

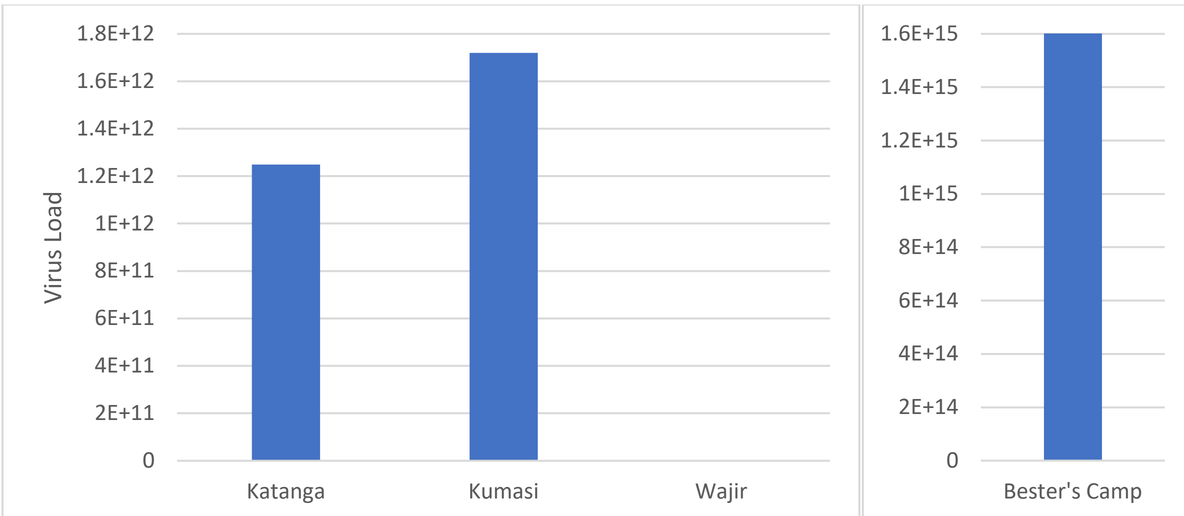

Figure 4.7 Virus load that reaches groundwater

Sensitivity Analysis

The results of the sensitivity analysis are shown in Figure 4.8. The removal rate of viruses and the fecal flow velocity have the greatest impact in the amount of virus reduction in pit latrines. The effects of longitudinal dispersivity were limited and a variation of the parameter up to double of its initial value will not produce any significant change to the total virus reduction.

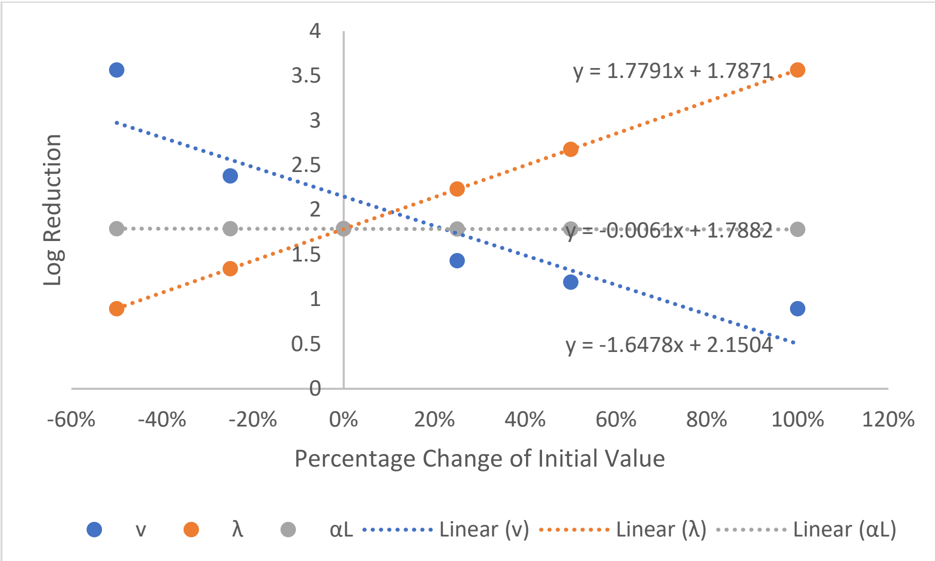

Figure 4.8 Sensitivity analysis of model parameters for a 3m pit latrine

Discussion

Sensitivity Analysis

The sensitivity analysis indicates that variation in the removal rate of viruses has the largest impact on the reduction of viruses in pit latrines and soil followed by fecal flow or pore-water velocity and longitudinal dispersivity. The significance of the removal rate can be seen from equation 4.2 where under steady-state conditions if the removal rate is zero, there would be no virus reduction. The results of the sensitivity analysis can also be confirmed by the results of field studies that show virus reduction as the main determining factor for the removal rate (Deborde et al., 1999; Schijven et al., 1999). For a more accurate prediction of virus removal, there is a need for more research to obtain parameter values of sorption and inactivation under different conditions (Schijven & Hassanizadeh, 2000).

Model Simulation

The loading rate of viruses is primarily dependent on the prevalence of the infection. Assuming that Bester's Camp has the same population as Wajir, pit latrines in Bester's Camp would still have 5.58 x 10^{16} rotavirus particles less than those found in Wajir. The actual virus load in pit latrines is likely to be higher in real pit latrines because healthy individuals that do not show any symptoms can also excrete viruses through their feces, whom are not accounted for in the model (Madeley, 1979). The highest amount of virus reduction can be found in the pit latrines of Katanga and Wajir as they are relatively deep, allowing viruses a longer time to settle, adsorb, desorb, and inactivate. A pit latrine of 3m—the deepest pit latrines found among the four case studies—can potentially reduce viruses up by up to 2 log; however, there are some pit latrines in Uganda that are over 8m deep (Reed, 2014) in which case they can reduce viruses by up to 5 log.

In all the cases except for Bester's Camp, the amount of virus reduction was more prominent in the vadose zone than in pit latrines and this is due to the fact they are much deeper. It was estimated that 50-90% of the total virus reduction between the surface and groundwater occurs in the vadose zone and therefore constructing pit latrines in areas with a deeper water table will be more effective at reducing virus concentrations in groundwater. The opposite was shown in the case for Bester's Camp and can be explained by their shallow pit latrines, which does not give enough time for viruses to adsorb and inactivate before they reach the bottom of the pit. Furthermore, the soils in the area of Bester's Camp were found to be relatively sandy with a very small proportion of clay, which are better at retaining viruses between particles.

In several countries including the Netherlands, United States, Canada, and parts of Australia, a minimum of 4 log reduction of viruses are required by law from the pollution source, in this case pit latrines, to the water source (CBCL, 2011; Dunn et al., 2014; NSW, 2015; Sarkis et al., 2013; Smeets et al., 2009). A minimum of 4 log reduction is required not only for drinking water but for other purposes such as farm water and firewater (Sarkis et al., 2013). The performance target for rotaviruses in relation to raw water recommended by the World Health Organization is 6 log and 8 log reductions for high- and low-income countries, respectively (WHO, 2011). The different standards are due to the difference in the severity caused by rotaviruses as a larger proportion of the population in low-income areas are under the age of five and are at a risk of rotavirus infection (WHO, 2011). According to the WHO guidelines, the groundwater in Wajir would be the only safe water to use for human consumption and other purposes. The water that first infiltrates into the saturated zone in Katanga, Bester's Camp, and Kumasi would require a further log reduction of 4.1, 7.2, and 3, respectively, from the point of entry to groundwater to the drinking water well for safe consumption. Improving the containment of pit latrines, building pit latrines in areas with a deep water table, or increasing the setback distance between pit latrines and drinking water wells are some of the potential solutions to achieve the recommended virus log reduction for safe water use.

Chapter 5: Discussion and Conclusion

Limitations and Recommendations

The literature review presented an overview of the current state of knowledge regarding models on virus emissions from pit latrines to groundwater. There are currently no pit latrine models on virus infiltration to groundwater due to the lack of knowledge on processes occurring in pit latrines and required parameters for modelling. The overview provides a better understanding of what is lacking and what is required to develop an accurate model in the future.

Simplicity of pit latrines and model inputs

The model simulated assumed that the default pit latrine used in this study to have similar characteristics to that of silty clay soils. In real pit latrines, however, the contents that fill it are much more diverse and are likely to have different effects and interactions with viruses than in soils. To simplify the modelling, the contents were assumed to be homogenous and only feces were accounted for as the input in the model. Pit latrines usually have non-homogenous properties as they may contain wastewater and domestic waste such as plastics, bottles, and blankets (Nwaneri, 2009). Therefore, the source of viruses in pits cannot be said to solely come from fecal matter (Brouckaert et al., 2013). Furthermore, viruses undergo seasonal variations and the concentration excreted through feces can vary at different times of the year (Moe & Shirley, 1982). In the colder seasons of autumn and winter, adenovirus, astrovirus, and rotavirus are more prevalent whereas in hotter summers enteroviruses are more common (Moe & Shirley, 1982). Therefore, different theoretical layers in pit latrines have been suggested (Nwaneri, 2009), as shown in Figure 2.1, and viruses may have different rates of adsorption and inactivation in each layer; however, quantitative data for parameters are still lacking and cannot be incorporated in the model.

Fecal matter is the main source of viruses, but viruses can only be transported through suspension in the liquid phase. This means that viruses can only reach groundwater as urine and other wastewater infiltrate through the pits and the vadose zone. More research is needed to determine the solid-liquid proportion of the pit latrine contents and the interaction between the two phases throughout the pit column. Once there is a better understanding of the fecal flow mechanics it would be possible to also explore virus fate and transport in different types of pit latrines, including dry pit latrines, flush toilets, dual pit systems, lined pits, as well as pit latrines with other interventions such as the addition of additives such as oyster shells, ash, and wood chips, which are commonly sprinkled in the case of dry toilets to fend off insects and minimize unpleasant odor (Magri et al., 2013).

Other aspects to consider are the possibilities of overflowing and the emptying frequency of pits—which were excluded in this model due to a lack of data. The overflow of fecal matter, pit effluent emptying frequency and method determine the number of viruses that are removed from the pit and will therefore affect the virus concentration that infiltrates into the subsurface. The model only accounted for the vertical movement of viruses without any horizontal flow—which is useful for estimating the most conservative concentration of viruses that can be used for virus risk management as it is the fastest way viruses reach groundwater—however, for a more accurate evaluation of virus concentration, horizontal flow of viruses in and out of pit latrines must also be examined.

The vadose zone

The model assumed homogeneity of the vadose zone and did not account for the water flow and transport mechanisms that also influence the speed and path of viruses that are carried along with water in the soils. Water generally flow faster in larger pores, which is characteristic of sandy and gravely soil, but it depends on the level of saturation. Pores that are partially or completely filled with water allow faster movement of water down and across the soil media due to the adhesive and cohesive properties of water (Hendrickx & Flury, 2001). Modelling viruses in areas with high precipitation can be further complicated by the regularly rising and falling of the water table. Unlike arid areas where the water table remains relatively stable, wet areas usually have high groundwater recharge and the fluctuation of the water table causes viruses to redistribute in the soil (Holden & Fierer, 2005). The transportation of viruses is also affected by the heterogeneity of soils. Viruses can rapidly bypass the topsoil by traveling in soil cracks, root channels, and burrows created by other soil organisms (Hendrickx & Flury, 2001).

Virus Transport Model Parameters

As shown in the literature review in Chapter 2 and 3, the most commonly used model for simulating virus survival over time is the first order exponential one-parameter model even though they are not the best representation of virus decay. Microbial models developed over many years have shown that pathogen survival in different environmental settings do not follow this linear pattern (Moe & Shirley, 1982; Pesaro et al., 1995). The model presented in this paper provides a more accurate measurement than the one-parameter model by including solute transport mechanisms and sorption. The combination of inactivation and removal rates with the 1D-advection dispersion equation allows a more detailed estimation of the total virus removal from pit latrines to groundwater than the first order exponential model; however, the parameters to account for this model are limited. The parameter data is mostly obtained from laboratory experiments. The currently available parameters depend on the experimental conditions and it is therefore difficult to apply them in different settings. The adsorption parameters, which determine the removal rate of viruses, for batch experiments are of little use in predicting virus adsorption in column or field experiments because of the highly variable conditions including soil heterogeneity and differences in experiment methods and tools (Schijven & Hassanizadeh, 2000). More research is required to develop parameters that account for reversible sorption for different environmental conditions.

The simulated model presents a linear decline of virus reduction with the depth of the pit and the vadose zone in the case of steady-state conditions. However, several column and field studies have shown that virus reduction with travel distance is not linear as reduction rates can be initially higher (Schijven & Hassanizadeh, 2000). One study showed a 1 log reduction of bacteriophages PRD1 and M1 after a travel distance of 0.94m through a sandy aquifer, but only an additional 1 log reduction in the following 1.6m (Bales et al., 1997). In another case for RNA bacteriophage, there was a 3.8 log reduction after 2m of dune infiltration, but only 0.83 log reduction in the next 2m (Schijven et al., 1998). Another uncertainty arises from the longitudinal dispersivity parameter that was kept constant in the simulation. Results from field studies have shown that dispersivity for viruses decrease with distance (Schijven et al., 1999). This non-linear behavior can be explained by soil and viral heterogeneity. There are more sites for adsorption, thereby increasing removal, in the uppermost layers of pit latrines and soil.

The findings of the literature review allowed the development of a preliminary model for virus emissions from pit latrines to groundwater. A further examination of pit latrine processes and the effects of soil and viral heterogeneity are required to develop more accurate parameters and improve the prediction of virus reduction from pit latrines to groundwater. However, given the data that is currently available, the foundation for modelling viruses in pit latrines and the vadose zone provided by this study can be used for groundwater management and as a guide for further research in this area.

Conclusion

This study presented a model for quantifying virus emissions from pit latrines to groundwater based on a literature review that shows the current state of knowledge on virus fate and transport in pit latrines and the vadose zone. The issues addressed in this paper were: (1) the processes influencing virus emission in pit latrines, (2) the processes influencing virus emission in the vadose zone, and the (3) development and application of a model that quantifies these processes in different case studies.

Pit latrine

The current knowledge on the processes occurring in pit latrines is lacking. A conceptual theory of processes occurring in pit latrines and a theoretical framework of how different layers are formed within a pit have been suggested; however, they have yet to be validated by other studies and are currently unquantifiable. So far only one study has attempted to model pathogen decay in pit latrines. The pathogen decay is modelled using a first order exponential decay equation. Using this linear, one-parameter approach may simplify the processes in pit latrines and may therefore not be the best representation of virus decay in pit latrines, but it may provide information that is currently unavailable or difficult to collect through field studies.

The vadose zone

The overview of the available literature showed that the vadose zone has been studied more extensively than pit latrines. The processes occurring in the subsurface and the interaction of soil particles with viruses are well known and several models exist. The main processes that affect virus fate and transport are adsorption and inactivation. Adsorption can be described by the Langmuir or Freundlich isotherm, which are both equilibrium models. Inactivation of viruses can be modelled using first order exponential decay. Non-linear models, which account for irreversible sorption, were found to be more accurate as they had a better match with the data obtained from field studies. These processes are influenced by the chemistry of the soil, including soil pH, ionic strength, organic matter content, moisture content, temperature; and virus properties, including surface characteristics and isoelectric point. While many models both linear and non-linear exist, some of the factors have been difficult to quantify and are not all addressed in the models. The existing non-linear models use the 1D-advection dispersion equation for solute transport to predict virus fate and transport in the subsurface.

Model simulation

A model that quantifies virus emissions from pit latrines to the vadose zone was developed based on the literature review. Due to the lack of data, the content of pit latrines was assumed to work in the same way as soils, and taking this into account, the 1D-advection dispersion equation coupled with inactivation and removal rates in the form of log reduction was used to calculate the virus reduction in pit latrines and the vadose zone. The model was applied to four urban areas in Africa that exhibit different characteristics such as the depth pit latrines and the type of underlying soil. Generally, deeper pit latrines and thicker vadose zones enhance virus reduction due to longer travel time of viruses. Clay soils are much more effective at reducing virus concentrations than silty or sandy soils. In most cases, the depth of pit latrines (1-10m) is minuscule compared to that of vadose zones—which can be as deep in 1000m in arid zones—and thus most of the total virus reduction can be attributed to the subsurface.

This study shows that there is a general need for more research, especially for pit latrines, to better understand processes related to virus transport and to develop parameters that can more accurately predict virus emissions from pit latrines to groundwater. The preliminary model presented in the study may help support planners improve risk management by finding suitable locations for pit latrines and setback distances of drinking wells, especially in urban areas where overcrowding and poor sanitation deteriorates water quality. Furthermore, the overview and model presented in this study can support future studies on virus emissions from pit latrines to groundwater and in the development of a more accurate and representative model.

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