TRANSFORMATION OF FAECAL SLUDGE IN VIPS: MODELLING FILL RATE WITH AN UNSTEADY-STATE MASS BALANCE

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ABSTRACT

Hygiene and sanitation is crucial for the health and productivity of the growing communities without access to running water and flush toilets. Pit latrines are a popular alternative to western-style toilets in developing countries. A scientific understanding of pit latrines could help improve global sanitation. A detailed chemical analysis was completed on the contents of two ventilated improved pit latrines (VIPs) operated under similar conditions in the eThekwini Municipality. Samples were taken from recorded pit depths and analysed for moisture, ash, Total Kjeldahl Nitrogen (TKN), free and saline ammonia (FSA), chemical oxygen demand (COD) fractions, total phosphorous and orthophosphate. The pH and alkalinity of the samples were also measured. The data was correlated with depth. A depth-age relationship was inferred from the characterisation of the contents and the assumption that fill rate was approximately constant and ash content persists at all depths in the pit.

A model of the fill rate of the pits was developed. The parameters relate to the unbiodegradable material input and the rate of degradation, which varies based on moisture content, soil porosity, temperature and other influences. With biodegradation, dehydration and compaction, the pit content is reduced to a quarter of its volume as fresh excreta. On average, a quarter of the pit volume is composed of unbiodegradable household solid waste. When a volume of rubbish is included with the volume of degrading faecal sludge, the VIP lasts approximately 15 years. When no rubbish is present, the VIP will take more than 25 years to fill. Removing rubbish from the pit would extend the functioning life of a VIP.

TABLE OF CONTENTS

List of Tables

List of Figures

Abbreviations

ADM1	Anaerobic Digestion Model No. 1
ATP	adenosine triphosphate
CH_4	methane
CO_2	carbon dioxide
COD	chemical oxygen demand
COD_b	biodegradable COD
COD_p	particulate COD
COD_{pb}	particulate biodegradable COD
COD_{pu}	particulate unbiodegradable COD
COD_s	soluble COD
COD_{sb}	soluble biodegradable COD
COD_{su}	soluble unbiodegradable COD
COD_t	total COD
COD_u	unbiodegradable COD
DMWS	Durban Metro Water Services
DWA	Department of Water Affairs (post May 2009)
DWAF	Department of Water Affairs and Forestry (pre May 2009)
EWS	eThekwini Water and Sanitation
ff	fresh faeces
FSA	free and saline ammonia
GIS	Geographic Information System
GPS	Global Position System
MDG	Millennium Development Goals
N_2	nitrogen gas
NH_2	amine group
NH_3	ammonia
NH_4^+	ammonium
NO_3^-	nitrate
NO_2^-	nitrite
O_2	oxygen molecule
TKN	Total Kjeldahl Nitrogen
UD	urine diversion toilet

UDHR	Universal Declaration of Human Rights
UN	United Nations
VIP	ventilated improved pit latrine
WRC	Water Research Commission of South Africa

1 Introduction

On 28 July 2010 access to safe drinking water and sanitation was recognized as a basic human right by the United Nations General Assembly. The recognition of these rights for all humans gained legal standing on 30 September 2010 when the United Nations Human Rights Council acknowledged that the right to water and sanitation is an essential part of adequate living standards. The 25th article of the Universal Declaration of Human Rights (UDHR) which was adopted by the General Assembly on 10 December 1948 includes the phrase "Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family." Although the Declaration is not a treaty, it is used as the basis of binding international laws and is cited as the obligation the international community has to all people. On 30 September 2010, the rights to water and sanitation were unquestionably included in all documents and laws referencing the UDHR as defining basic human rights. This reaffirms the responsibility of society to strengthen efforts to provide water and sanitation to all people. The further recognition of what an adequate standard of living entails removes the sense of charity previously associated with providing these essential rights; it has become an obligation without excuse of failure.

Thirty nine percent of the world population, 2.6 billion people, currently do not have access to improved sanitation facilities. Almost the entirety of this population lives in developing regions. All but one percent of the people in developed regions use improved sanitation compared to just over half in less developed regions (GEO 2010). In 2000, 189 countries signed a United Nations Millennium Declaration with the sole purpose of eliminating extreme poverty within a target timeline of fifteen years. The United Nations set forth the Millennium Development Goals (MDG) for 2015 to help track progress with concrete objectives. Included in goal seven is the aim to halve the total world population without access to safe drinking water and basic sanitation. Ten years later and over halfway to the target date, the United Nations reported the progress of the MDG. Accordingly, the world is not on track to meet the sanitation goal. Sub-Saharan African is behind schedule to meet the drinking-water goal as well. Following the current projected trend, the world will have 2.7 billion people without access to basic sanitation in 2015. If efforts to relieve those without improved sanitation are strengthened and the world is put on track to meet the MGD, it will have one billion fewer people without substandard sanitation. Tragically this still leaves 1.7 billion in need. In 2006, one billion people still practised open defecation. Southern Asian and Sub-Saharan Africa are the regions with the largest populations without access to improved sanitation facilities (WHO and UNICEF 2010). While progress is being made, in order to meet the sanitation goal the rate of improvement will need to triple in the next 5 years, which seems unlikely considering the areas that were helped first were those with easiest access and the most resources.

A motivating yet tragic reality is that on average one child dies from a water-related disease every 15 seconds. Most unsafe drinking water is caused by faecal contamination in developing countries (WaterAid 2009). Access to basic sanitation facilities not only provides a sense of personal dignity, but also a hygienic means of disposing toxic material. Approximately half of the world population is now living in urban regions due to the growing struggles of rural life. The urban migration is driven by the desire for a healthier life with more opportunities. Denser population causes a higher concentration of human waste deposited in urban and suburban areas. In 2005, just over one third of urban inhabitants in developing countries lived in slum conditions (United Nations 2008). If there is a sanitation system in place, it is most likely under-maintained and misused in the overcrowded slums of developing countries. The drive to remove the disparity in equality across the world must be intensified. In the meantime, the move to improve the sanitation of those living in poverty must become a priority, with specific attention on the urban poor. Overflowing latrine pits or ditches in an urban setting have a higher chance of people coming in contact with faecal matter than in a rural setting. The servicing of full pit latrines is more critical when located in a metropolitan area with compact settlements and dense population compared to more sparse developments (DWAF 2007). In this study, the pits are from dense developments with a high risk of contamination.

In 1994, the Department of Water Affairs and Forestry listed ventilated improved pit latrines (VIP) as the minimum acceptable level of sanitation in accordance with the goals of the Reconstruction and Development Programme (DWAF 1994). In 1997, Durban Metro Water Services (DMWS) was created to provide the metro area with drinking water and sewer essentials. The water development plan proposed by the eThekwini Municipality undertook the task of providing free basic sanitation facilities to every household within the municipality by 2010 in agreement with the South African Government Strategic Framework for Water Services. The eThekwini Municipality includes the entirety of the city of Durban and surrounding areas. In late 2000, the old jurisdiction of Durban was expanded from 1 366 km^2 with a total population of 2.5 million, to 2 297 km^2 home to 3.5 million (Gounden 2008). Of the 3.5 million inhabitants in the eThekwini Municipality, about 187 000 households of 5.5 people each, totalling approximately 1.03 million people, were without basic sanitation in 2004 (EWS 2004). Most of these households are located in suburban informal settlements. Bordering outside major economic centres, the level of development drops quickly and poverty is prevalent. The UN ranks South Africa as a “middle income country with an abundant supply of resources.” In 2008 South Africa’s Gross Domestic Product based on the Purchasing Power Parity was ranked 24th in the world by the World Bank. Despite these statistics and the recent urban development in localized areas, approximately 50 000 households in the eThekwini

Municipality were using VIPs as their primary means of human waste disposal in 2006 (WIN-SA 2006).

The eThekwini Municipality has undertaken the task of emptying the 50 000 VIPs on a 5 year cycle. The cost of emptying a pit, depending on removal method, content disposal location, accessibility of pit, and terrain, ranges between R 600 and R 1 000 per pit (WIN-SA 2006). Emptying 10 000 VIPs per year at R 1 000 per pit, the Municipality would spend R 10 000 000 per year emptying VIPs.

Although pit latrines have been a basic method of sanitation for centuries, little is known about the transformation processes taking place in them. Growing concern from the global and local communities regarding the health and safety of on-site sanitation has sparked an interest for a more detailed understanding of pit latrines.

A fraction of human excreta in pit latrines degrades over time. In practice, however, VIPs fill, indicating the rate of degradation of the material in VIPs is slower than the rate of input. Wastewater treatment plants, where western-style flush-toilet waste is treated, have been studied and modified extensively. There are many methods and adaptations of centralised treatment that are widely used and well understood (Zakkour et al. 2001). Similar investigations can be undertaken to improve understanding of VIPs and make them a viable and sustainable option for areas where water scarcity, underdeveloped infrastructure, and lack of funding does not support flush toilets. The degradation processes in VIPs must be understood in order to effectively manage the contents, design efficient vault dimensions, understand the groundwater pollution potential, quantify the effects of pit additives, quantify the effect on urine diverting VIPs, and improve operating conditions. By examining the chemical composition, VIP content can be described in terms of the biological processes that take place in the pit from the time material is added to the time of sampling. Additionally, the VIP filling rate may be modelled based on the pit content, conditions and design.

2 Problem Statement

Ventilated improved pit (VIP) latrines are used by innumerable people in developing countries. However, little is known about the condition of pit contents. A more detailed understanding of the degradation processes occurring in VIPs will enable a more efficient and cohesive management of pits. The processes inside and bordering VIPs are lacking the depth of scientific understanding that is necessary for effective operation, both economically and hygienically. Better knowledge of the VIP system could reduce the costs of construction and maintenance, therefore providing improved sanitation to a broader scope of society. This information can be used to reduce the health risks associated with use and emptying of VIPs. However, pit latrine design cannot progress toward scientific relevance and application unless the accumulation and degradation within are understood. Buckley et al. (2008c) proposes a series of layers and associated processes within VIPs. This study's approach is to verify characterisations of VIP content from previous studies and model the content with regard to the mechanisms effecting the transformations and/or transportation of the content. An outcome of this work is to provide an understanding of pit latrines to assist policy makers and sanitation practitioners recognize the significance of changes to policies regarding design, maintenance and disposal, and how these policies can influence filling rates, human health risks, and environmental pollution. To do this, a quantitative and qualitative understanding of what happens in the pits and how this influences the characteristics of pit contents is needed.

2.1 Aims of Study

By examining layers in an exhumed pit and deducing how the content transforms, the way in which VIP latrine content in the eThekwini Municipality condense and degrade is assessed. The specific objectives include:

- To determine the chemical composition of the VIP at the different stages of degradation, herein referred to as layers
- To obtain a baseline understanding of the chemical transformations in the VIP
- To examine factors that play a role in VIP degradation
- To develop a model of the biological degradation in a VIP
- To make recommendations on pit design and use to maximize pit lifespan
- To predict the average characteristics of pit latrine contents as they exist at the time they are emptied

2.2 Hypothesis

The two primary hypotheses for the aforementioned aims are:

1. If the contents of a pit latrine are characterised in terms of biodegradable organic, non-biodegradable organic, inorganic material, the particulate and soluble fractions of each of these categories and water, the biological and physicochemical processes in a pit latrine cause changes in the relative amounts of these fractions. These changes occur through dehydration (via vaporisation or leaching of water), leaching of soluble components and biological degradation of biodegradable components.
2. From characterisation of each of these fractions at different depths of the pit, where each depth represents a different age of pit sludge, the mechanisms that brought about the observed change can be inferred. From these inferences, a model of the pit can be developed.

3 Literature Review

Chapter 1 outlined the need for thoughtful action considering the world sanitation status. Although VIPs have been around for centuries, little quantitative research has been done to unveil the mysteries of why some pits fill faster than others. This chapter considers past studies that are relevant to this one and what they reveal through their correlation. Examining the history of the VIP, fill rate studies, and what is known about the contents and processes in a VIP, along with concepts used to model wastewater treatment plants, the Literature Review will provide a basis for comparison and a direction for this study.

3.1 Excreta

Human excreta are composites of waste matter discharged from the body such as sweat, urine and faeces. The majority of the excreta in VIPs consist of faeces and urine. The makeup of these components is an essential element to determine the degrading processes in VIPs.

Research shows the nutrient concentration differs based on diet, but within a standard range shown in Table 3.1. The average amounts of nitrogen, phosphorous and potassium found in excreta from Chinese, Haitian, South African, Ugandan, India and Swedish populations were calculated based on calorific intake from Food and Agriculture Organisation of the United Nations and equations derived by Jönsson & Vinnerås (2004) based on in-depth data on Swedish excreta and is shown further broken down in Table 3.2 and Table 3.3.

Table 3.1: Mean Total Nutrients in Excrement (Jönsson et al. 2004)

	Average Nitrogen [kg/person/year]	Average Phosphorous [kg/person/year]	Average Potassium [kg/person/year]
Faeces	**0.39**	**0.15**	**0.4**
Std Dev.	0.11	0.05	0.07
Urine	**2.83**	**0.31**	**1.1**
Std Dev.	0.81	0.07	0.16
Total	**3.23**	**0.46**	**1.5**
Std Dev.	0.82	0.09	0.17

The South African diet of the average VIP user consists of white bread, margarine, mielie meal, yams, squash and chicken. In general the diet is low in essential vitamins, minerals and whole grains. A significant portion of human excrement is composed of consumed nutrients. The presence

of nutrients in excrement makes it valuable fertilizer and with modern knowledge and technology this use is becoming more applicable. Between 88% and 97% of faeces by dry weight is organic matter and between 65% and 85% of urine by dry weight is organic matter (Sobsey 2006). Considerable variances in diet changes the composition and ratios present in faeces and urine which potentially affects the rate and form of degradation.

3.1.1 Faeces

The average Swedish adult excretes about 50 litres of faeces per year. This value varies considerably from population to population based on the digestibility of the diet. Populations with less digestible diets produce a greater mass of faeces per year. A larger proportion of nutrients are excreted in the faeces of less digestible diets relative to more digestible diets, such as the Swedish diet as found by Jönsson. The table below compares the average wet masses of nutrients found in faeces of people from various countries. The South African nutrient yield is similar to the Swedish values, both in the higher half of the countries presented.

Table 3.2: Faeces Nutrients reproduced from (Jönsson et al. 2004)

	Nitrogen [kg/person/year]	Phosphorous [kg/person/year]	Potassium [kg/person/year]
China	0.5	0.2	0.5
Haiti	0.3	0.1	0.3
South Africa	**0.4**	**0.2**	**0.4**
Uganda	0.3	0.1	0.4
India	0.3	0.1	0.4
Sweden	0.55	0.18	-

3.1.2 Urine

The average adult excretes between 500 and 550 litres of urine a year and children under 12 years excrete about half as much. Digested soluble nutrients are excreted via urine. Less digestible diets have a lower percentage of total nutrients in urine than faeces (Jönsson et al. 2004). Urine is approximately 99.5% water. The majority of the remaining 0.5% is made up of urea, chloride, sodium, potassium, creatinine, dissolved ions and organic compounds (Putnam 1971). Table 3.3 compares the nutrients found in the urine from people across 6 countries. Haitians consistently

have the lowest nutrient mass produced while the Chinese excrete the highest mass nutrients per capita in their urine. South Africa digested nutrient amounts as measured in urine are relatively high, especially in comparison to other developing nations. The South African diet ranges widely with each distinct population. These data are a compilation of populations within South Africa. It is difficult to compare South African dietary data to others because it varies significantly based on the population. However, as shown below, the nutrient content in the best available South African diet data is similar to that of the Swedish population. The Swedish excreta data is used as assumptions for calculations in this study as the best available data.

Table 3.3: Urine Nutrients compiled from (Jönsson et al. 2004; Mara 2004)

	Nitrogen [kg/person/year]	Phosphorous [kg/person/year]	Potassium [kg/person/year]
China	3.5	0.4	1.3
Haiti	1.9	0.2	0.9
South Africa	**3.0**	**0.3**	**1.2**
Uganda	2.2	0.3	1.0
India	2.4	0.3	1.1
Sweden	4.00	0.37	-

3.2 On-Site Dry Sanitation

The benefits of proper sanitation are innumerable. Improved sanitation enhances the communities' social outlook by providing privacy which increases self respect and dignity. Proper disposal also benefits the environment by protecting the soil and streams from nutrient contamination. Safe disposal of excreta improves the health of the community by limiting exposure to dangerous pathogens. Many micro-organisms commonly found in fresh faeces are known to cause disease. Because bacteria require specific conditions to survive, many faecal bacteria die-off when outside intestines. However, exposure to fresh faeces increases the potential of infection of the bacteria that persist. Not all pathogenic bacteria die-off at a rate that makes handling and disposing of excreta from collection vaults safe, even after a year. *Enterobacter spp* and *E. Coli* were found in excreta from urine diversion toilets in the Philippines after 6 months in a dehydrating storage vault (Itchon et al. 2009). *Ascaris* ova, despite worsening conditions, remain viable even up to a year (Itchon et

al. 2009). Faecal matter several years old may contain infectious pathogens and contact should be avoided (Trönnberg et al. October 2010).

3.2.1 Characteristics and Requirements of Sanitation Systems

When a community is in need of a sanitation upgrade, the characteristics of the sanitation system employed should be decided based on the particular requirements of the community. The designs considered should match the resources available. Resources to note include the volume of water present and available, the terrain and ease of accessibility, maintenance services available, social practices and awareness of the users and the short and long term financial situation dedicated to the community's sanitation. The following are brief descriptions of the defining characteristics for broad sanitation categories.

- On-site sanitation disposes of the waste at or very near to the point of generation.
- Off-site sanitation transports the waste to another location to be treated and disposed.
- Dry sanitation does not depend on water to transport waste material. If transportation is necessary in a dry sanitation system, methods such as vacuum trucks and scooping buckets are used.
- Waterborne sanitation uses water as a fundamental part of disposal usually to transport the excreta to another location and to dilute the waste.

On-site dry sanitation is a viable option where water is in short supply and funds may not be available to create and maintain a sewerage system to transport the waste material to another location (Geurts 2005). On-site dry sanitation must be carefully managed due to the high risk of contaminating a drinking water supply. Where water is scarce, surface water is often a source of drinking water. If excreta are not properly contained, precipitation runoff can rapidly contaminate entire rivers and lakes. Additionally, groundwater can be easily over-pumped. Over pumping pulls water into the drinking water system before it has been thoroughly filtered from bacteria, viruses and protozoa by surrounding soils and plant roots and settled in an aquifer. High concentrations of contaminated waste can overload natural filtering mechanisms and inevitably enter groundwater (WHO 2003). The cross-contamination of drinking water supplies and sanitation waste disposal is a real threat. However, the conditions in many developing countries call for on-site dry sanitation.

3.2.2 User Profile

The conditions associated with on-site dry sanitation result in the users nearly always being of a low socio-economic level. These sanitation systems exist in both rural and urban settings. Rural communities comply better with the needs of on-site sanitation. Dispersed development allows for

land buffers between drinking water sources, farming soil and waste disposal sites. On-site sanitation is more likely to be hygienic and safe because of increased physical distance between waste disposal and other daily interactions with possible points of contact in less concentrated communities. However, due to increased densities in low-income housing areas located in the suburbs, disposal of waste away from living quarters is expensive and, if done improperly, can create more of a hazard in transit. Transporting excreta increases the possibility of system collapse by extending the system and a spill event which could increase the affected areas (Abrams 2003; OXFAM 2009).

There are two main on-site dry sanitation user groups:

1) Sparse rural communities:

    - An off-site treatment system does not have the required technical support to function. Not only financial needs contribute to ruling out off-site treatment, but most treatment plants require a minimum waste load to sustain microbe activity and reliable maintenance. Additionally, the community may be out of reach of a sewer network.
    - Wet sanitation is commonly not an option because of the high demand for water. Communities may also lack the infrastructure and density for proper disposal of wet sewage or the water necessary to transport waste. On-site dry sanitation is economical and can be treated in small quantities.

2) Dense suburban communities:

    - The population is constantly transforming. The low-income sprawl outside of cities gives way to haphazard construction with little organisation. These circumstances make it difficult to establish piping or infrastructure necessary for an off-site or wet system.
    - On-site dry sanitation conveniently confines the excreta, reducing the risk of exposure and contamination without requiring water conveyance or technical maintenance. Although a relatively isolated system, there are still space restrictions in dense development compared to rural communities. On-site dry sanitation requires emptying which can be difficult with limited space.

3.2.3 Criteria

In the eThekwini Municipality, the minimum charge to connect to an existing sewer is more than R 5 000. This does not include the continual charge per volume of additional effluent into the

sewage disposal system which varies based on the location of the suburb (eThekwini 2010). For many low-income households, paying a sewerage bill every month is not a priority or even possible. The cost of constructing a new VIP was about R 3 000 in 2008. The eThekwini Municipality provides the owners of lined VIPs one free emptying service in a five year rotation (Gounden 2008). To have a VIP emptied outside the Municipal emptying cycle, the VIP owner would pay R 120. Extra charges exist depending on accessibility of the pit. If used properly, VIPs should easily last the Municipality's current rotation of 5 years (Still 2002). The cost of emptying VIPs depends on the pit dimensions, location, necessary emptying equipment, and disposal requirements. The most costly pits to empty are typically narrow and deep, situated in densely constructed areas on steep terrain and require off-site disposal. The eThekwini Municipality budgets between R 600 and R 800 to empty each pit in the metro area (DWAF 2007). Comparing the connecting costs and monthly fees of the sewer system to the cost of constructing and emptying a VIP, a VIP is more economical even without including the household hardware costs of the water based system. Additionally, the sewer infrastructure in or near informal housing has not worked well historically due to lack of maintenance, improper use and vandalism. House hold waste is commonly flushed into the pipes which causes frequent blockages. Illegal, slipshod connections are made to the sewer system (Gounden 2008) which can overload the system, causing further damage. Water pipes are intentionally broken to release Municipal water for free, private use such as cooking, irrigation and washing. The pipes are also removed and sold. Current economic status and past practical experience indicates that eThekwini Municipality is best suited to focus efforts on providing decentralized sanitation as a minimum standard.

There are various types of on-site dry sanitation. Three common alternatives to a VIP are a pit latrine, a composting toilet and a urine diverting toilet.

1) A pit latrine is a pit either constructed above the ground but more commonly dug in the ground and used to collect excreta. The basic cost of a pit latrine is the work needed to dig a hole; the remaining cost depends on the sophistication of the superstructure, if any. These are primitive and simple but cost effective options for waste management, although not the most efficient at degradation or supportive of a hygienic environment (WHO 2011).

2) A composting toilet uses aerobic degradation to treat the waste. A bulking component such as sawdust is added after each use. The waste pile needs to be turned regularly for thorough treatment. Composting toilets can decrease the volume of waste 5 to 10% of the original volume. In 1990 commercially made composting toilets cost between 1 500 and 5 000 US$

depending on material and capacity. Composting toilets require diligent maintenance to function properly (Fritsch 1990).

3) A urine diverting (UD) toilet separates faeces from urine and stores them separately for different treatment methods and uses. Most UD toilets have double chambers to alternate use once one is full. The excrement is ideally used as fertilizer. UD toilets are usually maintained by the user which makes them a cheaper option by reducing maintenance costs. In 2007 commercially available UD toilets cost between USD 150 to 200 (Terrefe and Edstrom 2007). UD pedestals manufactured locally in Durban by Envirosan Sanitation Solutions cost USD 47 in 2011 (ZAR 350).

3.3 Ventilated Improved Pit Latrines

The concept of improved sanitation is to separate human excreta from human contact. Human waste is hazardous because of its propensity to carry viral and bacterial diseases. VIPs have specific construction characteristics which qualify them for the minimum level of sanitation in South Africa as illustrated in Figure 3.1. What differentiates VIPs from regular pit latrines is the superstructure and a vent pipe with a fly screen. The superstructure provides shelter from the elements and privacy for users. The door and sealed walls provide safety by preventing small children, animals and debris from falling into the pit. The superstructure also functions to control the odour and prevent flies from entering through the open hole of the pit. Further odour reduction is from the circulating air caused by the sun heating the black vent pipe. Additional movement of air across the top of the pipe from wind causes a slight pressure drop due to the Venturi effect which draws air through the pedestal, into the pit headspace and up the vent pipe, venting odours above head height. Flies breeding in the pit are drawn up the pipe by the daylight at the top opening, where they are trapped by the screen. This prevents the flies from being present and escaping when the toilet lid is opened. The flies eventually die, unable to escape from the pit. The drastic reduction in fly nuisance reduces the spread of disease by insects (Mara 1984; Smith and Scott). The dark coloured vent pipe and fly screen make VIPs more hygienic and more comfortable to use. The cover slab and pit collar are required to prevent collapse when in use and when emptying. The seat cover prevents flow of pit air into the superstructure and reduces additional light in the vault that would detract the flies from being drawn into the vent pipe, away from users.

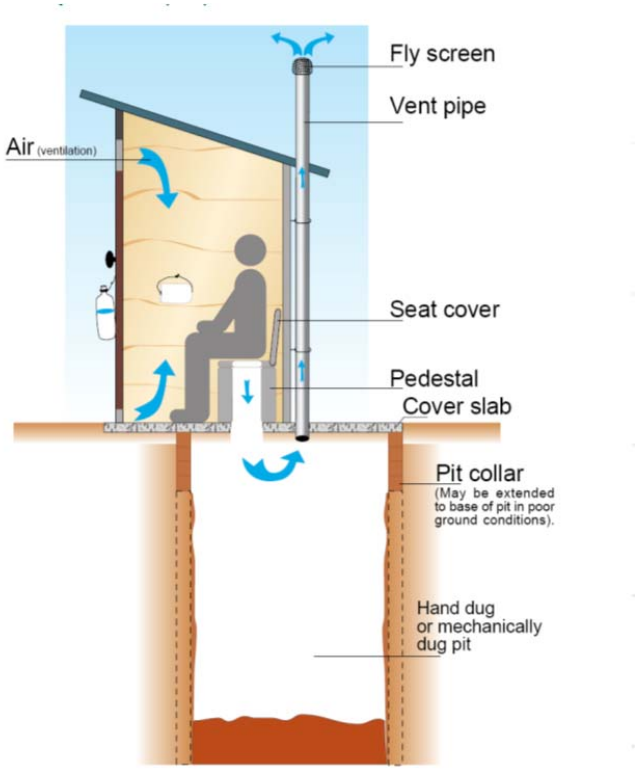

Figure 3.1: Sketch of VIP essential characteristics (DWAF 2002)

Two types of VIPs structures are frequently cited; the single-pit and twin-pit. Both consist of four main components:

1. a pit
2. a foundation and cover slab
3. a superstructure
4. a vent pipe with fly screen

The twin-pit designs have two compartments that share a single superstructure. When one compartment is full, it is covered and the other is used (Mara 1984). The eThekwini Municipality contains many different construction designs that affect the overall functionality of the pits. The VIPs in eThekwini are single-pit and include the four necessities listed by Mara (1984) though not all have the same dimensions or even general shape. Figure 3.2 is a photograph of a typical eThekwini rectangular single-pit VIP in the Savana Park Township. The vent pipe, superstructure and cover slab over the pit are easily identifiable. An example of a VIP design constructed in the Municipality can be found in Appendix III.

Figure 3.2: Typical VIP. Savana Park, Durban November 2009- VIP A998

3.3.1 Design

The design of a VIP has a significant impact on its performance. Variations can be made on depth, width, cross-sectional shape, materials, lining, alignment and positioning among other characteristics to improve the functionality.

The four main mechanisms of material transfer in a VIP are the following (WRC 2007):

- the filling of the pit with all deposited material such as faeces, urine, anal cleansing material, and rubbish
- the transfer of water into and out of the pit
- biological transformations
- pathogen die-off

Each of the above has the potential to vary because of the design of the VIP.

3.3.1.1 Physical Characteristics

Although the use and environment surrounding each VIP influences the performance, it is possible to regulate the pits with standard designs. The VIPs examined as a part of this study have lined pits due to the potential danger of collapse when emptying unlined pits. The instability of unlined pits puts the technicians emptying the pit and the users at risk. A lined VIP has a pit collar, commonly

concrete or brick, built into the ground along the depth of the pit to prevent collapse. Most lined pits have intentionally missing bricks or gaps to allow percolation. There is rarely lining on the bottom of the pit which allows water both into and out of the VIP through the soil interface (Terrefe et al. 2007).

Moisture enters the pit through:

- the toilet opening via a human function such as depositing excreta, enemas, purging or washing, or from precipitation if the pit is uncovered
- the pit walls from surrounding ground water
- the pit bottom if a high water table is present or seasonal

Moisture leaves the pit by:

- evaporation through the top
- seeping through the pit walls
- seeping through the pit bottom when the surrounding soil is drier than the pit contents

If moisture is added into the pit at a higher rate than it is transferred throughout the pit content, water will pool on the surface (Hillel 1998). Stagnant water in tropical climates poses a particular threat as a breeding ground for insects that carry diseases. However moisture rich conditions in a pit also induce rapid degradation which makes moisture an important component to sanitation. The surrounding soil interface (the boundary of investigation for this study) affects the moisture within the pit. Whether moisture moved from the pit to the surrounding soil or vice versa depends on water potential gradients. The availability of moisture held in soil solids can be measured in pore pressure of suction when the pore pressure is negative. Moisture suction represents the force needed to extract the water molecules from the soil particles and is the sum of the adsorption forces between the water and soil particle surface and the surface tension of water (Perrier et al. 1960; Hillel 1998). The difference in pore pressure of suction between pit content and soil will determine the direction flow. The movement of water in and out of the pit is dependent on water potential gradients and soil permeability. The direction of flow, combined with evaporation rates and moisture addition rates will control whether the pit is wetter or dryer. Because moisture content in a pit is affected by the soil permeability at the pit content and soil interface, the behaviour of the VIP is affected by the soil type. The characteristics of soil surrounding a VIP should affect the design and characterisation of a VIP.

Other studies that measured VIP moisture content within the eThekwini Municipality found a range from 0.3 to 0.8 g water per g wet sample. The pits with lower moisture content were located on

sandy soils and were sampled after dry spells. The wetter samples were tested after rainfall and were located in more clay-like soils or on higher water tables (Buckley et al. 2008c). The local topography as well as the soil types can have a dramatic effect on the moisture content within the pit. VIPs on high water tables are susceptible to be saturated during rainy seasons (Iwugo 1981). Those on hillsides will have different flow patterns than those in valleys or flat ground. Sandy soils will allow for quicker water flow while pits dug in clay soil will have slower water transfer. The topography, climate and soil type play a significant role in the degradation of excreta in pit latrines due to their influence on the moisture content. Pits with higher moisture content are reported to have increased rates of decomposition and stabilisation compared to pits with low moisture content, therefore further reducing the final contributing volume of each excreta deposit (Buckley et al. 2008c; Montessuit 2010; Franceys et al., 1992). The increased degradation rate of high moisture content contributes to a slower rate of accumulation.

3.3.1.2 Fill Rate

It is estimated that an average of 0.05 m^3 of faecal waste accumulates per person per year, as derived from Jönsson's work. The fill rate not only depends on the faecal matter produced, number of pit users and the pit size, it depends on the other materials deposited and the degradation rate of these materials once they are in the pit. It was found that the filling rate of pit latrines varies greatly; between 10 and 100 litre per person per year (Bakare 2008)**.** The degradation rate in turn relies on the conditions in the pit and the biological activity taking place throughout the pit. The table below summarizes the range of results from 5 studies of pit filling rates.

Table 3.4: Observed pit fill rates (adapted from Still 2002)

Location	Reference	Age of Latrines [y]	Number of Sites Monitored	Number of Visits	Mean Pit Volume [m^3]	Range of Filling Rates Observed [l/p/y]	Mean Filling Rate [l/p/y]
Soshanguve	WRC Report	3	11	14 in 28 months	1.96	13 to 34	24
Bester's Camp	City of Durban Report	4	159	3 over 25 months	3.16	18 to 121	69
Mbila	Partners in Development	5	11	1	2.83	10 to 33	19
Mbazwana	Partners in Development	11	19	1	3.40	14 to 120	29
Inadi	Partners in Development	11	25	1	2.00	14 to 77	34

3.3.2 Emptying and Disposal

Sludge removed from pits must be handled carefully due to health risks from pathogens. Various types of removal technique have been tested on the range of VIPs and sludge consistencies which occur in the region. Methods such as mechanical pumping, vacuuming, and manual emptying have

been explored under different conditions and sludge types (Scott and Reed 2006). The geographic situation of VIPs in the eThekwini Municipality has shown that manual pit emptying is the most cost effective method (Bakare 2008). Workers use shovels, spades and pitch forks to manually remove the pit contents, which allows them to work on steep slopes, narrow passages or other locations that would be difficult for large machinery to access (DWAF 2007).

Once the method for sludge removal is established, the method of disposal must be resolved. There are two options for disposal; on-site and off-site. On-site disposal requires sufficient space and a low water table. Generally, a second pit is dug next to the VIP and the material emptied from the VIP vault is buried in the adjacent pit in the ground. The Municipality currently requires 200 mm headspace of soil covering the fill to prevent surface contact and at least 50 m distance from a drinking water borehole. Previous research suggested that under proper temperature and pH conditions, faecal matter can stabilise within 2 years (Scott et al. 2006). However, recent research in urine diversion waste shows that the *Ascaris* ova, a typical infectious helminth, can survive in pit conditions for at least 5 years (Buckley et al. 2008a). Caution is still necessary when handling excreta after years of decomposition. Given that disease-causing organisms, formerly expected to have died-off, are present in the bottom of urine diversion pits after several years, it is crucial that the human-to-pit-content interface be reduced as much as possible, no matter the age and expected stabilisation of the excreta.

Off-site disposal can be a complicated procedure as it requires transportation, screening and an adequate treatment method. Methods of transportation include buckets, tanks, trucks and bags, all of which put workers and the public at risk of contamination. Once the contents have been transported they are treated through incineration, trenching, pond treatment, composting or by diluting into a wastewater treatment plant (O'Riordan 2009). If accessibility and capacities allow, faecal sludge can be transported to a centralised treatment facility or discharged into the sewer system at intervals with dilution (Tilley et al. 2008). This type of disposal becomes complicated because faecal sludge from dry on-site sanitation is of the order of 700 times more concentrated with conventional constituents such as TSS and TKN than typical municipal wastewater. Although the volume addition of VIP solids relative to the treatment capacity of the treatment works may be a small fraction of the volume received from flush toilets, the contaminant loading is the constraining factor (Still and Foxon in press 2012). It is possible to eliminate the selected bacteria in the treatment plant and overload the system when VIP contents are added. The treatment plant can fail as was done when VIP sludge was added to the Genazzano Sewage Works in KwaZulu-Natal when solids in the feed was increased due to additional VIP sludge and the nitrifiers were washed out of the system (Eco-San 2011). The bacterial loading must be calculated and diluted so

that the treatment can maintain the proper microbes for sludge digestion. Koné and Strauss (2004) suggest the use of satellite plants where pre-treatment of the sludge by separating the liquids from the solids would take place. This allows the liquids discharged into the sewer lines to be treated in a wastewater treatment plant while the solids would be treated at the satellite plant, which decreases transportation distance and cost (Koné and Strauss 2004). Overall, discharge into a wastewater treatment plant is not recommended. Due to the expenses and resources available, the VIPs in the eThekwini Municipality are disposed of using on-site adjacent pit burial when space allows.

3.4 Pit Conditions

Due to the engineered conditions of VIPs to increase airflow through the pit chamber, the top layer of material in the pit is exposed to air. The availability of oxygen denotes aerobic conditions and indicates that aerobic processes are likely to dominate the biological degradation in this region of the pit (Buckley et al. 2008c). This thin aerobic layer separates the rest of the pit content from open air, causing the remainder of the pit to be anaerobic.

3.4.1 Physical

The dimensions and shapes of VIPs vary greatly. The length, depth and width of pit vaults affect the processes, capacity and fill rate of the pit. **Figure 3.3** shows the cross-section of a typical VIP and the main components including the 4 layers in the pit. The VIP can be modelled with four layers of increasing thickness with depth. The top is a thin layer of fresh faeces in which aerobic degradation occurs quickly. Below that is a slightly thicker aerobic layer of partially degraded faeces, followed by an anaerobic layer as a result of being covered by the layers on top and in which slower anaerobic degradation occurs. The bottom layer is completely stabilised anaerobic material (Buckley et al 2008c).

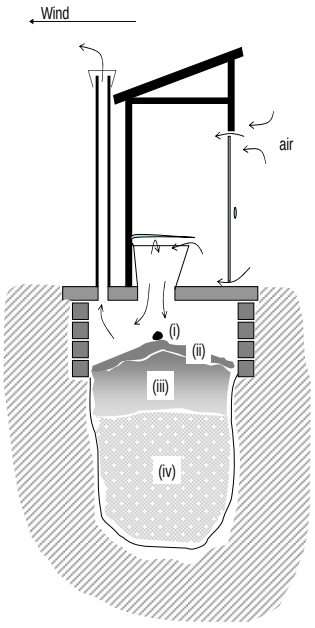

Figure 3.3: Side View of VIP and layers (Buckley, et al. 2008c)

The following design characteristics strongly influence the performance of a VIP.

1) Ventilation: All VIPs have vents but the efficiency of the vent determines the cycle of oxygen in contact with the excreta and therefore, the quality of the aerobic layer.
2) A lined pit will retain more water therefore increasing the moisture content, changing the texture of the solids and affecting the dominating processes.
3) The location greatly affects the flow of water into and out of the pit. A wetter pit can be easier to empty, depending on emptying technique.

The design plans of a rectangular single pit VIP used in the eThekwini Municipality can be seen in the plans in Appendix III. These are the standard dimensions used by the company Partners in Development (www.pidonline.org), as contracted by eThekwini. However, not all the VIPs in the Municipality fall under this design and it is not uncommon for VIPs to not be built to design due to restrictions of materials, location and variation in construction crews.

3.4.2 Contents

The content of VIPs varies widely from region to region and pit to pit. Some trends were noted during the emptying campaign throughout the eThekwini Municipality. Although the intended content of VIPs is human excreta, it is common to find a variety of rubbish materials in a pit latrine. Glass bottles, food wrappers, plastic bags, cloth blankets, magazine pages and soiled

clothes are examples of what is most commonly found in pit latrines in addition to the expected excreta and soft tissue toilet paper. It was estimated that rubbish unfavourable to VIP degradation contributes an average of 25% of the total volume of contents removed from the pit latrines (Still 2002). The proportion of household solid waste present in VIPs emptied the Savana Park vicinity is reported to be consistent with others at a quarter of the pit volume. This estimation is an observed average for the pits sampled and the surrounding area and it is consistent with the estimation by Still (2002).

The majority of VIP content consists of faeces and urine. The components of urine and faeces are outlined in the Section 3.1. However, pit content does not maintain the same composition as fresh excreta. As shown in Table 3.5, all the measured characteristics report a decrease in concentration from fresh excreta to the older aggregate pit content. The faeces and urine in the pit undergo transformation processes as discussed later in this chapter.

Table 3.5: Comparison of typical values of physical and chemical characteristics of pit latrine sludge and fresh excreta (Nwaneri 2009).

Parameter / Characteristics	Pit Latrine sludge	Fresh excreta (Faeces and Urine)
BOD [kg/p/y]	2.9	16
TS [kg/p/y]	33	40
TKN [kg/p/y]	1.8	3.7
Volume [l/p/y]	55	73
COD mg/L	20 000 to 50 000	-
COD/BOD	5 : 1	-

With proper VIP use, rubbish will not be present in the pit contents but not only excreta will remain. Anal cleansing material will still be found in the pit. Ideally this consists mainly of toilet paper as it is designed to degrade in these conditions. The Swedish population was found to use 8.9 kg of toilet paper per person per year (Jönsson et al. 2004). Although this study examines a different population with different toilet use habits, the mass of anal cleansing material is not an insignificant addition to organic matter. Magazine paper and newspaper are commonly used as anal cleansing material in VIPs because they are available scrap material serving an additional primary use while toilet paper may be an unbudgeted cost or simply unavailable.

3.4.3 Temperature

The temperature of pit contents can strongly affect the rate of chemical processes and biotransformations. Many factors such as geographic location of the pit, the season, and the time of

day affect the temperature. Temperatures influence the microbes as well as characteristics of the solids and the rate of gas transfer. Anaerobic digestion can be effective at a wide range of warm temperatures; from 30 to 60°C. However a constant temperature is important because the bacteria react poorly to temperature changes (Metcalf and Eddy 2003). According to the U.S. EPA, undergoing anaerobic digestion for a minimum of 15 days between 35 and 55°C or 60 days at 20°C will significantly reduce pathogens (EPA 1993). The majority of VIP content is anaerobic for years. The temperature of pits in eThekwini is 18 to 25°C (Moodley 2010). Under these conditions pathogens will be significantly reduced (Metcalf and Eddy 2003), although persistent pathogens may not be complete eradicated.

3.4.4 pH

Micro-organisms tend to be very sensitive to pH. Although they can survive in a broader range, the pH for optimum biological growth for methanogens is between 6.5 and 7.5. The rate of nitrification is more susceptible to the pH than the rate of denitrification. No major effect is noted on the denitrification rate between a pH value between 7.0 and 8.0. The pH generally increases during denitrification due to the production of alkalinity. Methanogen activity is only active around a neutral pH, between 6.8 and 7.4 (Metcalf and Eddy 2003).

3.4.5 Nutrients

Micro-organisms require energy, carbon sources, and a minimum amount of specific nutrients for growth. Each of these could be a limiting factor to inhibit or change microbial growth. Energy can be obtained from light or chemical reactions. Chemotrophs derive their energy from oxidation-reduction reactions. Heterotrophs derive carbon from organic matter and autotrophs use carbon dioxide. Converting carbon dioxide to new biomass requires more energy than converting organic matter which is why autotrophs usually produce less cell mass per gram than heterotrophs. There are several primary inorganic nutrients, micronutrients (named for their small quantities), amino acids and vitamins that also need to be present for microbial growth and biological degradation. Nitrogen and phosphorus are needed in greater quantities for biological treatment. One hundred g of cell biomass requires approximately 12.2 g of nitrogen and 2.3 g of phosphorus (Metcalf and Eddy 2003). To susceptible populations such as infants and the elderly, an excess of nitrate in water can be poisonous and deadly which is why nitrate is considered a potential contaminant of concern (EPA 2010). While some levels of nutrients are necessary for degradation, an excess can be harmful which is why the fate of these nutrients must also be taken into consideration.

3.4.6 Aerobic Processes

Aerobic respiration occurs when bacteria use oxygen as the electron acceptor to produce energy from nutrients such as glucose, amino acids and fatty acids. In typical wastewater treatment,

aerobic digestion is used to reduce a significant proportion of volatile solids. The retention time for sludge in an aerobic zone is commonly between 10 and 20 days or between 40 and 60 days if pathogen reduction requirements are to be met (Metcalf and Eddy 2003). With a typical number of users, a deposit in a VIP is aerobic for much less time than this.

3.4.7 Anaerobic Processes

Anaerobic conditions exist only when no oxygen is present, neither free nor bonded. Anaerobic respiration is less energy efficient than aerobic respiration, meaning it releases less energy. In anaerobic digestion, electrons move from one carbon atom to another within a molecule and the associated energy transfers are very small compared to that of anoxic or aerobic systems, hence the low available energy for growth. Obligate anaerobes, like methanogens, cannot exist in an environment with oxygen. After anaerobic digestion, the amount of remaining biodegradable material should be minor if the material is fully stabilised (Buckley et al. 2008c). Anaerobic digestion uses bacteria and archeae to break down biodegradable material and produce methane and carbon dioxide (FAO 1997). The process consists of four stages briefly described below; hydrolysis, acidogenesis, acetogenesis, methanogenesis.

Hydrolysis is the conversion of complex insoluble organic matter, like lignin, carbohydrates and proteins, to simple soluble compounds, such as fatty acids, sugars and amino acids.

Acidogenesis is the conversion of fatty acids, sugars and amino acids to simpler organic acids, propionate and butyrate.

Acetogenesis is the conversion of volatile fatty acids, the products of acidogenesis, into acetate.

Methanogenesis is the conversion of acetate to methane and carbon dioxide, to fully decompose the biomass.

Anaerobic digestion is important in breaking down carbon and nitrogen molecules to continue the carbon and nitrogen cycles. In anaerobic digestion, carbon is released as CO_2 and CH_4. A fraction is retained as inert organics and biomass, and a fraction is released as bicarbonate into the soil and groundwater. Nitrogen is released as ammonia from the biodegradation of nitrogen bearing organics. Little or no NO_x should be added to the pit therefore little or no N_2 should be produced but nitrogen fixation and nitrification/denitrificaiton is known to occur in the surrounding soil.

3.4.8 Microbial Energetics and Pit Latrine Additives

There are natural processes of degradation in VIPs as is evident in that the total volume of excreta deposited into a pit over time is greater than the total volume of the pit vault. A fill rate was reported to have decreased by more than 33% over two years according to one study that examined

VIPs from the second year in use to the fourth year (Still 2002). Assuming user practice remained approximately consistent over the two years, the pit content was degrading inside the pit as excreta was added.

Adding a solution to the sludge that could degrade the contents quicker and more completely would aid many sanitation problems. Complex molecules are constructed and broken down along different metabolic pathways which allows the rate of degradation and cell growth to function independently. Studies have been done to investigate the efficacy of pit latrine additives that claim to accelerate the rate of degradation. Although additives claim to lengthen a pit lifetime through chemical or biological means, there are no blind laboratory studies conclusively verifying this (Buckley and Foxon 2008; Buckley et al. 2008c; Foxon et al. 2008; Foxon et al. 2009; Montessuit 2010). There have been claims that the processes in pit latrines have been accelerated with additives but scientific backing is still needed and continues to be researched. The London School of Hygiene and Tropical Medicine are currently researching pit latrines to support the development of bio-additives and other technologies.

3.4.9 Process Biochemistry

Established transformation pathways have been studied largely through wastewater treatment technologies. An understanding of these processes will assist in the analysis of transformations within VIPs.

The nitrogen cycle is an important biogeochemical cycle that traces the transformations of nitrogen compounds. The diagram below, **Figure 3.4**, illustrates the possible pathways and forms of nitrogen in the environment while Section 3.4.7 discusses the fate of COD under anaerobic conditions. Of the possible pathways for nitrogen, only ammonification/biological decomposition will happen during anaerobic digestion, specifically at the hydrolysis and acidogenesis steps.

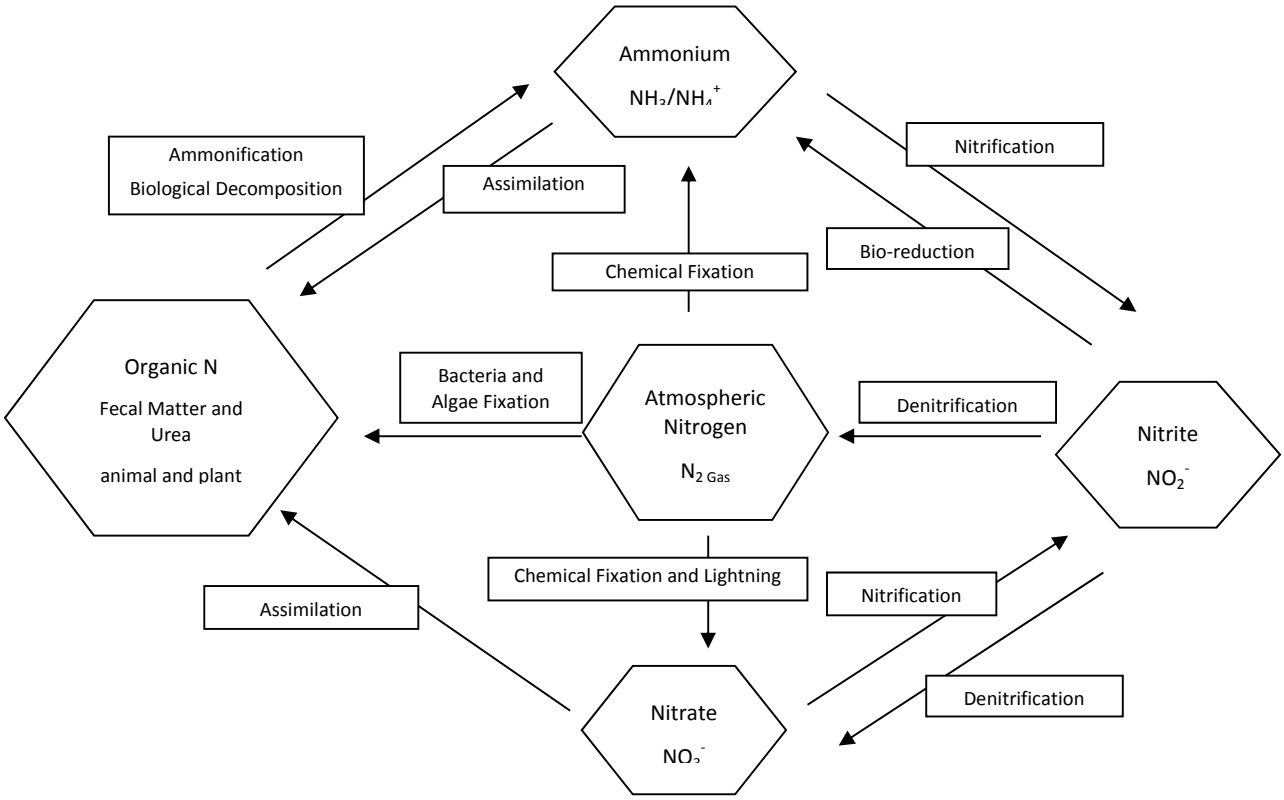

Figure 3.4: Transformations in Nitrogen Cycle

3.4.9.1 Ammonification

The organic nitrogen in faeces and urine, as well as in plant and animal organic protein, undergoes ammonification where it is converted to ammonia (NH_3) and ammonium ions (NH_4^+). The ratio between NH_3 and NH_4^+ produced depends on the temperature, moisture and pH of the environment. NH_4^+ dominates in pH values less than 8.5. Under aerated, warm conditions, between 20°C and 35 °C, enzymes readily convert the amino acids (NH_2) to ammonium. Nitrogenous compounds of dead organisms are hydrolyzed to amino acids which micro-organisms convert to ammonium. NH_3 is usual converted to NH_4^+, which is then excreted in urine. Urine consists of urea which hydrolyses to ammonium and produces alkalinity.

$$H_2N\text{-}COONH_4 \rightarrow (NH_2)_2CO_2 + H_2O \rightarrow NH_4^+ + HCO_3^-$$

Saline ammonia refers to the ammonium ion, NH_4^+. Free and saline ammonia (FSA) combined equals total ammonia. Ammonium, as a cation, is held strongly by soils and not easily leached by passing water (Scott 1989). This is important to note in the discussion of the accumulation and transportation of nutrient in the pit. The reaction responsible for the NH_3 and NH_4^+ ratio is as follows:

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$$

3.4.9.2 Nitrification

Under aerobic conditions, nitrifiers convert ammonia to nitrate. Nitrosomonas oxidize ammonia to nitrite. Nitrobacter oxidize nitrite to nitrate approximate three times faster than the ammonia to nitrate conversion. Therefore it is unlikely that a significant or even measurable amount of nitrite is present in the VIP. To oxidize 1 mg/L of ammonia to nitrate, the reaction requires about 4.6 mg/L of oxygen (Russell 2006).

$4NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$
$2NO_2^- + O_2 \rightarrow 2NO_3^-$

Nitrification removes alkalinity, reducing the buffering capacity of the substance and generally leading to a decrease in the pH of the material. For every part ammonium converted to nitrate, 7.1 parts alkalinity are used. The pH decreases quickly if alkalinity drops below 50 mg/L. Biological activity necessary for degradation decreases quickly once the pH is below 6.5 or above 9. At lower pH the production of N_2O and NO increases. The most efficient nitrification occurs when the temperature is between 20 and 30°C. Nitrification is practically halted by temperatures below 5°C or in excess of 50°C (Metcalf and Eddy 2003).

3.4.9.3 Denitrification

Under anoxic conditions, oxygen is not available; therefore selected heterotrophic bacteria break down organic material by transferring electrons to nitrate, ultimately converting it to nitrogen gas. This process is denitrification. The result of anoxic decomposition is CO_2 and nitrogen gas. Denitrifying bacteria include *pseudomonas, micrococcus, achromobacter and bacillus* (Russell 2006). The stoichiometric equation for denitrification is:

$NO_3^- + 6H^+ + 5e^- \rightarrow 0.5N_2 + 3H_2O$

NO_3^- + Organics + Heterotrophic bacteria $\rightarrow N_2 + CO_2 + OH^-$ (Alkalinity)

The electron donor for nitrate reduction can come from an added external carbon source, incoming excreta, or endogenous respiration of micro-organisms.

The denitrification rates of readily biodegradable COD (COD_{RB}) and slowly biodegradable COD (COD_{SB}) are different and therefore the quantities of each need to be considered when denitrification is taking place. The different fractions do not need to be considered when nitrification is considered because they do not affect the rate (Haandel and Marais 1981). The difference between COD_{RB} and COD_{SB} is the rate at which they can be biologically degraded, which depends mostly on molecular weight. COD_{RB} is made up of low molecular weight compounds or molecules whereas COD_{SB} is higher molecular weight molecules. From this, the

differentiation of the two is based on physical separation where COD_{SB} is considered particulate and COD_{RB} is soluble.

3.4.9.4 Assimilation

Assimilation is the conversion of nitrate or ammonium to plant protein organic nitrogen. Organisms must assimilate nitrogen into molecules as it is essential for growth. When plants or algae cannot independently perform nitrogen fixation, the plant roots absorb nitrate and ammonium ions. Nitrate is reduced to nitrite and then incorporated into glutamine and other amino acids for cell synthesis, shown in the equation below. The equation below uses $4NH_2$ which are the amine groups in amino acids and not glutamine.

$$2NO_3^- + 2NH_4^+ \rightarrow 4NH_2 + 3O_2$$

3.4.9.5 Fixation

Fixation is the conversion of nitrogen gas to other forms of nitrogen, but results in ammonium. Most fixation is done by symbiotic bacteria with the nitrogenase enzyme. The reduction of nitrogen gas to ammonia is an energy expensive process. The enzyme is easily disrupted in the presence of oxygen and frequently bacteria stop production (Zhou 2007).

$$N_2 + 6H^+ + 6e^- \rightarrow 2\ NH_3$$

3.4.9.6 Degradation Model

The basic mass-balance for biological treatment of waste is: accumulation = inflow – outflow + generation. A commonly used empirical formula for the five main organic fractions found in biomass is $C_5H_7O_2N$. With the addition of phosphorus it becomes $C_{60}H_{87}O_{23}N_{12}P$ (Metcalf and Eddy 2003; Brink et al. 2006; Ekama 2009). The combining of aerobic and anaerobic processes into one model is possible because unbiodegradable particulate organics under aerobic conditions are also unbiodegradable under anaerobic conditions. This simplifies the steady-state models by making it possible to calculate the unbiodegradable particulate fraction between aerobic and anaerobic conditions allowing for the plant-wide process mass balance (Ekama et al. 2006).

A COD mass balance would determine the outcome of the carbonaceous material at each level down the pit and therefore the processes that transform it by calculating the amount oxidized and the amount assimilated into cell mass (Metcalf and Eddy 2003). Readily biodegradable COD is quickly incorporated into the biomass while the slowly biodegradable fraction must be biologically degraded before it is incorporated. The hydrolysis of colloidal material can be up to four times faster than that of particulate material (Sophonsiri and Morgenroth 2004; Ekama 2009) . Therefore the size and composition of the particles greatly affect which processes and at what speed take place and at what rate.

4 Methodology

To obtain a better understanding of the biological degradation in VIPs, the content of two VIPs in the eThekwini Municipality were sampled. Samples were taken from each pit at four depths. In Chapter 5, Data Analysis, these depths will be related to an age based on their ash content. The chemical analysis and biodegradability of the pit content at each depth was determined using standard laboratory test methods, adapted for VIP waste. Each sample was analysed for moisture content, ash, phosphorous, pH, alkalinity, Total Kjeldahl Nitrogen (TKN), ammonium, nitrate and nitrite content. Additionally, the soluble, particulate and biodegradable chemical oxygen demand (COD) of each sample was determined. BOD measures the dissolved oxygen required for aerobic bacteria to break down organic compounds. The majority of pit content is anaerobic. Therefore biological oxygen demand (BOD) was not determined because it is not a determining factor for the hypothesis.

Without a validated method for measuring the unbiodegradable mass fraction in the pit, the ash component is measured and used as a surrogate for the inert fraction that is assumed to remain constant in mass over time. The unbiodegradable mass fraction in the pit is reported on a *per ash* basis to show the changes in the ash mass component. It is not possible to accurately age a sample in this type of study. However, if it is assumed that the mass of inert material in a sample deposited at a particular time (measured as ash) does not change with the age of the sample, but the mass of biodegradable material does, then the fraction of ash in the sample will increase with time in inverse proportion to the disappearance of biodegradable COD. Therefore, assuming the fraction of ash in the material added remains approximately constant over time, the ash content of an aged sample could theoretically be regarded as a surrogate measure of age.

This analysis is conducted under the assumption that the filling rate of VIPs is approximately constant during the filling period. Inferring the age of the sample from the ash content allows further filling rate analysis. Additionally, it is assumed that the ratio of ash to other fractions added to the VIPs remains constant during the filling period. Previous work suggests that ash content is not a particularly reliable measurement due to the high sample variance and difficulty in obtaining a small representative sample for use in analysis (Buckley et al. 2008c).The approach presented here assumes that the non-degradable fraction of any portion of material added to the pit will remain approximately constant and that changes will occur in the moisture and biodegradable content over time. The moisture content is measured at each layer and may be influenced by vaporization, leaching or groundwater inflow. The biodegradable fraction is measure at each layer and is expected to decrease with depth but the rate order is unknown. It is expected that the

unbiodegradable portion will become relatively larger as the age of the sample, or depth, increases and the biodegradable fractions will become relatively smaller.

Alkalinity, phosphate and nitrogen fractions are analysed at each depth and are expected to change as a result of leaching and biological activity. The changes in these analytes may provide some insight to the leaching and biodegradation mechanisms within the pit.

4.1 Samples

The variation of VIP form, use, setting and performance is extensive, not only throughout the world, but within the same municipality. This complicates the study of VIPs by adding many potential causes of variation in pit behaviour. The variation contributes to the extent of the information required to improve function and effectiveness but also represents the diverse conditions in which VIPs may be a viable solution.

4.1.1 Pit Selection

The eThekwini Municipality VIPs have several standard designs but many pits are not built to design making the variation of pit volumes within the Municipality extensive. A common design, found in eFolweni within the Municipality, is a cylindrical pit 2 m deep with an outer circumference of 4.9 m and wall width averaging 0.1 m thick, resulting in an approximate volume of 2.9 m^3. In Savana Park, the pits are rectangular; designed to be 2 m deep, 0.82 m wide, 1.72 m long, giving a volume of 2.8 m^3. The dimensions of the pits in this study were measured after the pits were emptied. Although both pits were constructed identically, the dimensions were different from the plans in Appendix III. It is found that pit depths beyond 1.5 m are difficult to empty manually without a person entering the pit (WRC 2007). The pits considered in this study have open block-work on all sides with an unlined base. The VIPs in eThekwini are numbered and their exact location is recorded using GPS (Global Position System). These data points can then be manipulated in a geographic information system (GIS) where information about the pit construction, age, and topography can be stored, found and manipulated (Gounden 2008). The location of water bodies and land contours relative to the pit has the potential to be useful in determining water flow in the surrounding soils.

The pits examined for this study were located within the same community and had very similar geography, climate, design and construction. This was done intentionally to eliminate sources of internal variation as much as possible. The pits were being emptied as part of the Municipal pit emptying programme. Both the VIPs selected were within 200 mm of capacity and located on hillsides with a low water table. VIP 1 was on the top of a steep slope while VIP 2 was in the middle of the hillside. Both pits had the same concrete block construction and were in

approximately the same condition with an intact superstructure. According to the community liaison officers, each pit had 7 users. Neither pit had been emptied before the sampling event during the municipal emptying.

4.1.2 Sampling

Two VIPs were sampled from Savana Park in May 2010, where the Municipality was currently emptying pits using on-site disposal. The samples were taken from four vertical layers as the VIP was emptied. Samples were collected at the top of the pit, 0.5 m down, 1.0 m down and at the bottom of the pit, 2.0 m down. A lined plastic container approximately 300 mm x 300 mm x 150 mm was filled for each sample. The depth difference between the first and second samples and the second and third samples was 0.5 m. The depth difference between the third and fourth sample was 1 m. The Municipality workers removed the back top slab covering the vault (Figure 4.1) and used spades and rakes to empty the pit. The excavated material was emptied into a hole dug on-site because space was available for the two sampled pits. The alternative would be to empty material into bins for transportation to a different site. The top layer sample was collected from the very first shovel off the peak of the sludge mound. The top layer consisted of the most recent deposits that were still exposed to the air. The height of the pit was noted on a measuring rod with 0.5 m, 1.0 m and 2.0 m noted in reference to the top of the vault. When the centre of the pit reached the next marked height, another sample was taken. The emptying technique involved some shifting of the pile and occasionally the pit content collapsed on itself. While sampling the emptiers were instructed to maintain as much order in the sludge layers as possible. Because of this, error for the centre two measurements is estimated around 300 mm while the top and bottom samples had negligible error. The samples were screened to remove large, obvious, non-faecal related material, such as plastic bags, cloth and broken glass so that the collected contents did not represent the pit contents with regard to rubbish content. This material was piled separately and used to visually estimate the quantity of rubbish present in each pit. Samples were stored in pre-labelled, sanitized and lined plastic containers with lids. Safety masks, gloves and field suits were worn during collection to protect from exposure shown in the Figure 4.1.

Figure 4.1: VIP emptying and sampling through the back opening

This study did not monitor moisture seepage in and out of the pit walls and floor via the surrounding soil. The pits examined had fully functional superstructures so that precipitation did not enter the pit chamber from the surface opening.

After observing the emptying of more than 20 VIPs in various regions in the eThekwini Municipality, the estimation of 25% of the total volume as non-faecal content by Still, 2002 is an adequate average estimation but can range between 10% and 40%. The two VIPs sampled were assessed by eye after emptying to be 25% household solid waste based on volume.

Because the Municipality was manually emptying pits, the VIP content was easily accessible. The goal of the municipal work was to empty the pit vault of all contents as efficiently as possible. Figure 4.1 shows the emptying and collection process out of the back opening of a pit, where the top of the vault has been removed to gain access to the pit content. This process did not also include removing the contents in order from top to bottom. Rakes were frequently used to collapse the top layers of the pit down towards the back opening for easier removal with a spade. On occasion, workers would put a rake down the toilet pedestal in the superstructure and push the piled material from the top because it is difficult to access from the back opening in the ground. When sampling, the sampler observed the strategies of the workers and estimated the in-situ location of the material being disposed at the time. The estimated error of these collections is summarized in Table 4.1 where the depth sampled is relative to the top of the pile in the pit. The top and bottom layers were collected with the greatest accuracy because a sample off the top of the pit is as

unambiguous as is a sample of bottom matter that remained undisturbed during the removal of the material above.

Table 4.1: Estimated error of sampling at specific depths down VIP

Depth Sampled	Estimated Error Each Side of Sample Depth
0.0 metre	50 mm
0.5 metre	250 mm
1.0 metre	300 mm
2.0 metre	50 mm

4.1.3 Transportation Safety

Four plastic containers with lids were sanitized, lined with plastic packets and labelled before arriving on-site. The sample collectors drove to a safe pre-designated location to meet the site supervisors before going on-site for safety reason. As the Municipal workers emptied the pit, they placed a full shovel of pit content off the top of the pit into a lined and labelled plastic box. Efforts were made to ensure soil and rubbish was not retained along with the faeces during collection. The plastic box was sealed and washed with 70% ethanol. A 70% ethanol solution was used to sanitize the boxes and equipment that may have been in contact with excreta before handling. The boxes were then taken back to the laboratory and immediately placed in the cold room for storage and preservation. The chemical analysis began immediately.

4.1.4 Chemical Analysis

All Standard Methods refer to Standard Methods for the Examination of Water and Wastewater, 19th Edition (APHA 1995) The sample solution used for COD, phosphorous and pH tests is a two part dilution resulting in a solution of 6 g wet sample per litre. A wet sample refers to a sample that has its in-situ moisture content and has not been desiccated. All tests were done in triplicate unless otherwise noted.

4.1.4.1 Solids

Solids were tested in accordance with Standard Methods 2540 (APHA 1995).

Total solids and moisture content were calculated from Standard Method 2540 B, by drying 30 g of sample at 105°C overnight (APHA 1995).

Volatile solids and ash content were calculated from Standard Method 2540 E by igniting the dried samples in a furnace at 550°C for 2 hours (APHA 1995).

4.1.4.2 Alkalinity

Alkalinity is a measure of the resistance of a solution to change pH through the addition of strong acid. Alkalinity is the buffering capacity of a solution that quantifies a solution's capacity to neutralise the addition of H^+ and OH^- molecules therefore maintaining a constant pH. The presence of bicarbonates or other compounds that combine with H^+ atoms increases the alkalinity of a solution by increasing the stability of the pH of the solution. It is usually expressed as the equivalent concentration (mg/L) of calcium carbonate ($CaCO_3$). Alkalinity was tested in accordance with the standard methods (APHA 1995). Each sample was titrated with 0.01 M HCl to a pH value of 4.5. The dilution used was 1 g equivalent dry weight of sample mixed to 1000 ml with distilled water.

4.1.4.3 pH

pH values for each layer were determined using the Standard Method 423, with a pH probe (APHA 1995).

All results are reported as mg analyte/ g wet sample.

4.1.4.4 COD

The chemical oxygen demand (COD) measures the mass of oxygen consumed per volume of material and represents the amount of organic material present. Different organic compounds require different amounts of oxygen to be fully oxidized. All COD tests were done in accordance with the Standard Method 5220 Open Reflux Method B (APHA 1995).

Total COD measurements were performed on samples diluted to 6 g wet sample/l.

Soluble and particulate COD were separated by centrifuging 30 ml of the 6 g wet sample/ l solution for 1 hour at 10000 rpm. The soluble COD was obtained by testing the supernatant. Particulate COD was then obtained by testing the pellet solids remaining in the test tube.

Biodegradable COD was determined using an 8 day aeration of diluted sludge samples and comparing the COD values before and after the 8 days of aeration.

4.1.4.5 Nitrogen

Nitrogen can be in reduced or oxidised form. Reduced oxygen includes ammonia, ammonium and organically-bound nitrogen and is measured as Total Kjeldahl Nitrogen (TKN) using Standard Method 420 A (APHA 1995). Oxidised nitrogen is present as nitrate and nitrite. The sum of reduced and oxidised nitrogen concentrations, reported as mg N/l, is the total nitrogen concentration of the sample.

Nitrate (NO_3^-) and nitrite (NO_2^-) were expected to have low values if at all present. Nitrate is tested according to Standard Method 418 B, using a nitrate electrode (APHA 1995).

Ammonium (NH_4^+) was determined using the Standard Method 417 D, via a distillation-titration method, also using 1 g dry weight equivalent sample diluted to 1000 ml with distilled water (APHA 1995).

4.1.4.6 Phosphorous

Total phosphorous and orthophosphates were determined using Standard Method 424 F, colorimetric method with ascorbic acid (APHA 1995). The methods for phosphorous and orthophosphates only differ in the digestion of the sample for total phosphorous to convert to the orthophosphate form to be analyzed. The dilution used was 5 g dry weight equivalent sample diluted to 1000 ml with distilled water.

4.1.4.7 Approach to data interpretation

Previous studies indicated that changes in pit content characteristics were due to biological decomposition of organics to soluble and gaseous products which exit the pit through volatilisation or leaching with liquid flow (Buckley et al. 2008b). Components that are originally soluble may also be leached out of the pit content with time. Because material is recurrently added to the top of the pit content, there will be a distribution of content age with the oldest, most stabilised at the bottom and freshest, least stabilised at the top. For the purposes of this study, the rate of addition of pit content is assumed to be constant.

Thus it was anticipated that analytes bound to biodegradable solids will show a general decrease in concentration per mass of material with increasing depth or age. It is not clear whether soluble analytes will increase, decrease or remain unchanged with depth since their concentration depends on the rate at which they are depleted by leaching compared to the rate of generation by solubilisation.

The ash content, the portion of solid material remaining after ignition at 550°C (Section 4.1.4.1), is assumed to remain associated with the material with which it was deposited in the pit; it is assumed to not undergo biodegradation or leaching. It is assumed that ash is not transferable or transformable, or that the rate of transfer is negligible. As other components degrade or leach out, the mass fraction of ash will increase because the overall mass of the material with which it was deposited has reduced, but the ash fraction has remained unchanged.

COD is a tool to determine the oxygen demand of the content imposed on the environment and as an indicator of what reactions are occurring. Biological processes reduce COD by converting COD bearing organics to CO_2 or CH_4 which exit via volatilisation, while solubilisation changes

particulate COD to soluble COD which can exit the pit via leaching. The basic fractionation of COD is shown in Figure 4.2. This reaction scheme is based on a combination of literature and the data from this study (Ekama 1984).

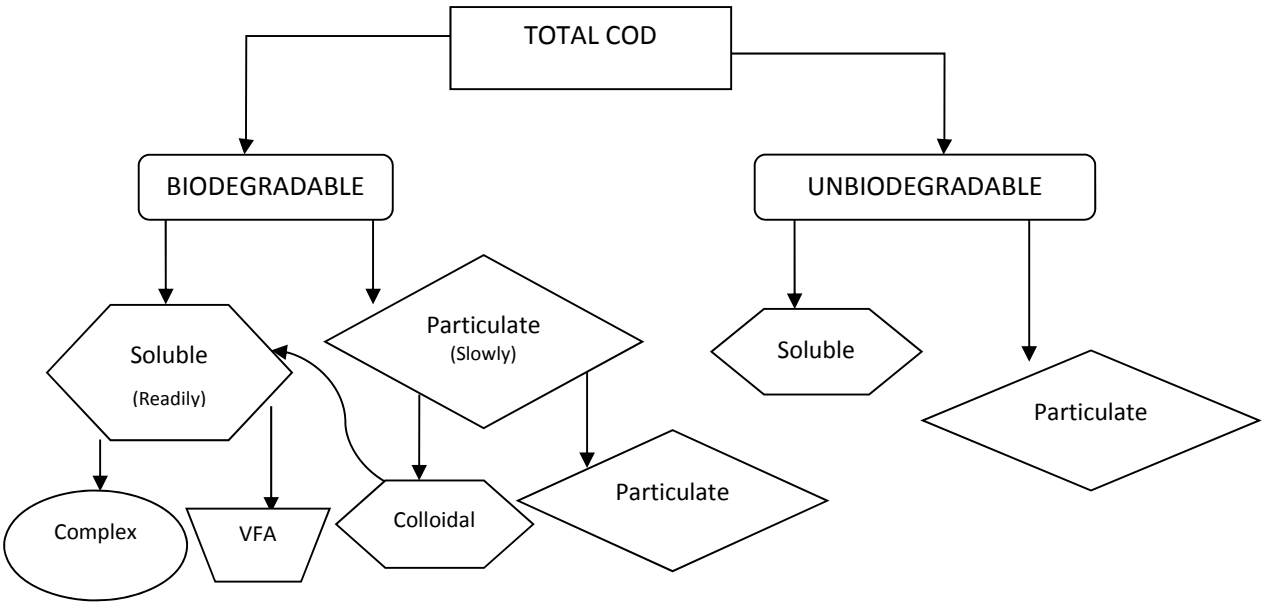

Figure 4.2: Characterization chart of fractionated COD

The fractionation of COD enables the path of the contents to be traced. The soluble COD will follow the path of the water flow. It is expected that the biodegradable COD will slowly degrade in the pit while the inert particulate COD will accumulate in the bottom of the pit (Wentzel et al. 1999; Buckley et al. 2008c). Inert particulate COD remains relatively unchanged while the surrounding material degrades or is transported. This causes the inert particulate to accumulate over time. Aging pit contents become enriched with inert particulate COD relative to the original feed because the biodegradable COD depletes with time.

5 Data Analysis

Two VIPs were sampled and chemically analysed. The pits were sampled on May 14 and May 17, 2010 in the Savana Park Township of eThekwini by the Municipal pit emptying team. The following measurements were taken in both pits:

- pH
- Alkalinity
- Moisture content
- Solids: Total, volatile and ash
- COD: total, particulate, soluble
- Biodegradable COD: total, particulate, soluble
- Nitrogen: TKN, ammonium
- Phosphorous: total, orthophosphate

Unless otherwise noted, the tests were analysed in triplicates (n=3). The data used for fresh faeces is taken from published data (Nwaneri 2009).

Raw data for all analyses are presented in Appendix I. The analyte concentrations are given per gram wet sample. The majority of parallel research is presented in g/g wet which allows for comparison however the data are presented here on an ash mass basis as discussed below.

5.1 Assumptions

Several assumptions are made in the analysis of this study where data were unavailable and either cost or time prohibitive. The assumptions that carry the most weight throughout the analysis are used in the ash mass balance from which fill rates and rubbish distribution are determined. This study assumes that the density of VIP sludge is constant throughout the VIP. The assumption that the density of fresh faeces is approximately 1 g/ml is based on general observation. This assumption makes 1 kg and 1 L of fresh faeces equivalent quantities of fresh faeces. Sample calculations are shown in Appendix II.

The ash concentration of fresh faeces is taken from data provided by Nwaneri (2009) at 0.11 g ash/g wet sample.

The average rate of 51 kg of fresh faeces per person per year taken from Jönsson (2004) was used to determine the average input into the pit which is used to calculate other quantities. Other assumptions include Jönsson's measurement of urine produced per person per year at 550 kg.

For the two VIPs used in this study, the community liaison officers indicated that 7 people used the pit and have been using the VIP since they were built in 1996. It is assumed in the calculations that the 7 users were consistent in use of the VIP and that the input rate of excreta and rubbish into the VIPs was constant.

The density of ash is estimated to be approximately that of silica at 2600 kg/m^3. The density of ash is used to convert the ash content from mass to volume. The density of rubbish is estimated at 1300 kg/m^3 by averaging the densities of glass, plastic, cotton fabric and cardboard.

The non-degradable rubbish constitutes 10% by volume of the input to the pit. Because biodegradable material in depleted from the pit content with time, this rubbish fraction, although not changing in mass becomes a larger fraction of the material in a full pit, constituting 25% by volume of the full pit content.

The ash concentration of fresh faeces, excreta production rate and number of people all relate inversely with the fill rate. If the number of people, ash concentration of fresh faeces or excreta production is doubled, then the length of time to fill the pit is halved.

These assumptions are based on previous research and are the best possible estimation for this study. Values of ash content in fresh faeces and the mass of fresh faeces produced per person per year vary widely in different populations and should be adjusted accordingly where appropriate.

5.2 Wet vs. Dry vs. Ash Measurement Basis

Data is measured on a total sample basis, and much of the literature data is presented in this way (Foxon, K. M., et al. 2009, Chaggu, E. J., et al. 2007, Jönsson et al. 2004). However, presenting the data in terms of mass dry sample or mass ash may be more informative. Figure 5.1 demonstrates the importance of differentiating between reference units using alkalinity data as an example.

Because of the varying concentrations of moisture and volatile solids in each depth of the pit, the alkalinity per gram wet points have a substantially different shape from the same measurements of alkalinity converted to a per gram ash basis.

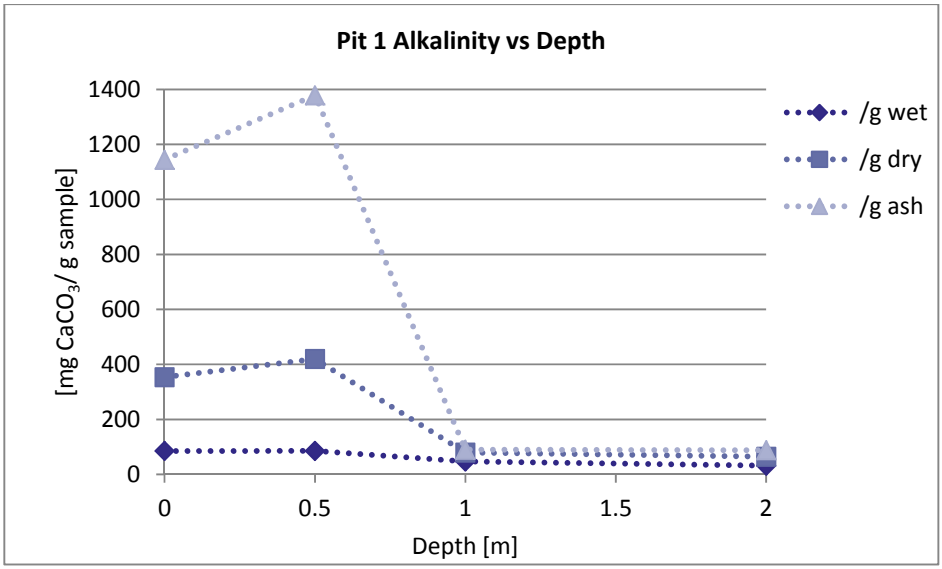

Figure 5.1: Comparison of the same measurements of alkalinity as mg CaCO3 per g wet sample, dry sample and ash to show the importance of comparison.

Analysing data on a wet basis represents the in-situ mass proportions in the pit. However the data will be diluted with independently varying moisture contents as discussed in Section 5.3.1.

Data in g/g dry is the concentration per total solids and is useful to see concentrations without the influence of moisture. Analysing data on a dry basis eliminates the variances in moisture content, but it does not take into account that the ash content should be systematically increasing. Analysing data on a dry basis does not report the value relative to a non-changing property.

Analysing data on an ash basis would show the constituents against a theoretical constant in the pit. However, as discussed in Chapter 4: Methodology, ash measurements have a high variance from sample to sample. Using the ash content as a denominator for the other measured fractions increases the variance in these measurements and may limit the information in the data.

The majority of the data in this study are presented on a g ash basis to capture the changes in each characteristic relative to a mass fraction of the sample that is assumed to be constant over time. Concentrations in g/g ash are used in this study to show trends of compaction of a characteristic compared to the compaction of the total mass.

5.3 Analytes

Although most of this analysis is with regard to the ash basis data, the measurements used to calculate the analyte concentration per g ash are first discussed to reveal the underlying patterns, variances and transformations in presenting the data in this form.

5.3.1 Moisture

Moisture content is the amount of free water found in a substance. Figure 5.2 shows the top sample in both VIPs had similar moisture concentrations to fresh faeces, which is 0.77 g/g wet, and relatively unpredictable variations further down in the pit. The y-error bars do not extend past the symbol used. The x-error bars are estimated based on possible mixing and sampling techniques.

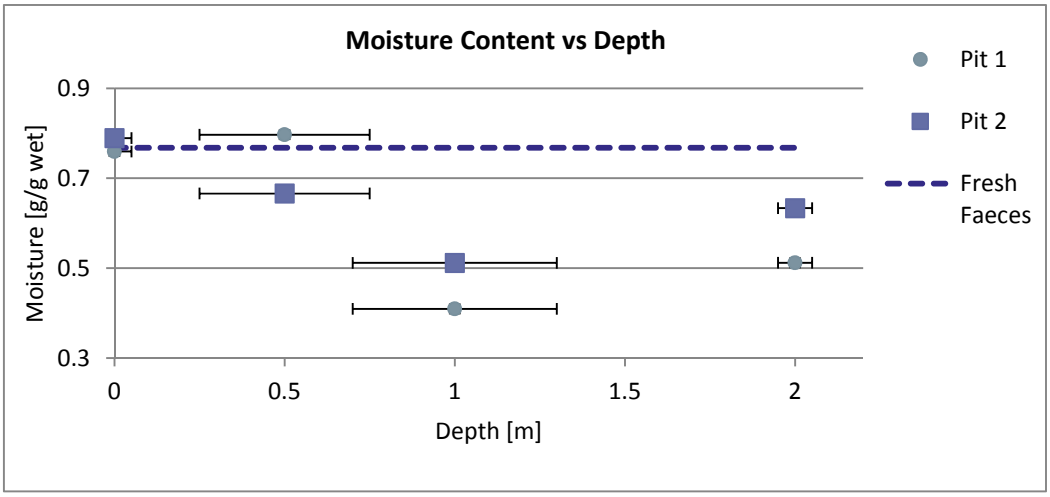

Figure 5.2: Moisture content at point samples for Pit 1 and Pit 2 with moisture content of fresh faeces for comparison in the dashed line.

Published research shows that decreasing moisture levels with depth is not directly correlated to the age of contents but is rather associated with the ground water conditions (Bakare 2008). Moisture content variation is not directly related to biodegradation at the levels found in an active pit but does influence other characteristics.

As shown in Table 5.1, if no water were to enter or exit the pit once the excreta was deposited through the surface opening, Pit 1 would have 6 000 kg and Pit 2 would have 5 400 kg of water strictly from faeces input. Not considering the moisture content of urine, the total moisture in the pits would be 1 600 kg and 1 700 kg respectively. This is 3.7 and 3.1 times less than if all the moisture from the fresh faeces input had remained in the pit and not including additions from urine and precipitation. The two pits contain an average 3.4 times less moisture than if the pit were filled with fresh faeces alone. It is therefore clear that significant volumes of moisture exit the pit during its lifetime; an amount on the order of 30 000 kg per pit over a period of approximately 14 years.

A study to examine the potassium levels throughout the pit would be useful to trace the flow of urine. The top sample's moisture content is similar to that of fresh faeces in both pits which could indicate several concepts:

- Urine largely drains away, leaving the surface moisture content the same as faecal moisture content.
- Some urine drains away from the surface and some moisture evaporates, leaving the net effect on the surface moisture content the same as faecal moisture content.

Table 5.1: Moisture Mass Balance

Mass Balance	Units	VIP 1	VIP 2
Urine In*	[kg]	28 000	28 000
Moisture from Faeces In	[kg]	6 000	5 300
Total Moisture in VIP	[kg]	1 600	1 700
Moisture loss	[kg]	32 400	31 600

*assuming 50% of urine produced by the 7 VIP users is deposited in the VIP and that all 7 users average 550 kg of urine a year.

Figure 5.3 shows the moisture concentrations for both VIPs on an ash basis. The majority of the moisture contained in excreta is lost in the first metre of material in the pit.

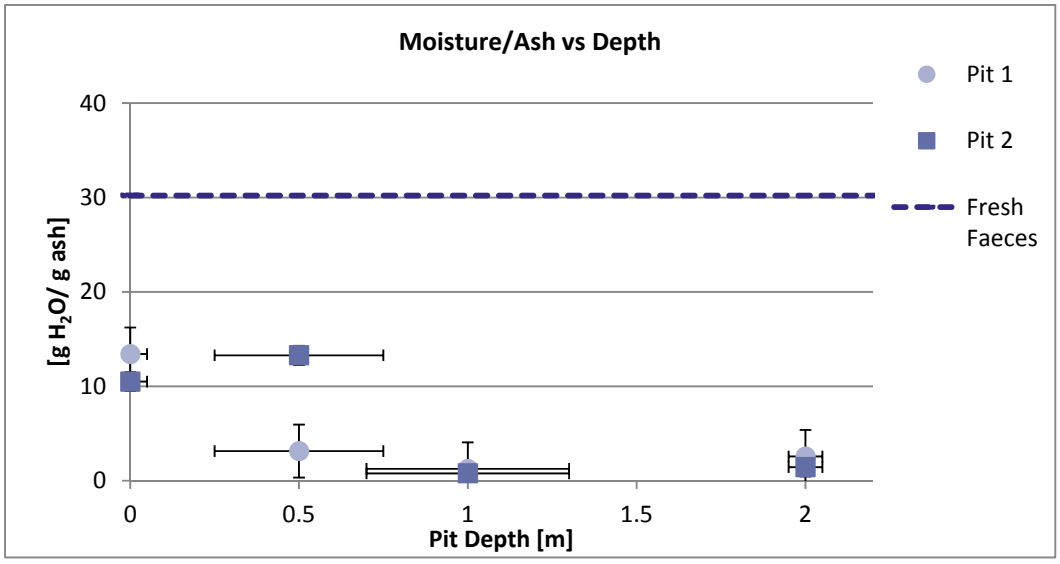

Figure 5.3: The Moisture/Ash ratio plotted against depth in both pits

5.3.1.1 Ash

Ash is the remaining mass in a dish after ignition at 550° C for two hours and represents the non-organic, non-transportable portion of material added to the pit latrine. The pit content may be compressed through the following means:

- Loss of moisture: leaching and evaporation

- Loss of solids: dissolution and leaching
- Gas escape: entrapped air escaping, production of methane, carbon dioxide escaping
- Biodegradation of pit content

New excreta are constantly accumulating from the top. The only user access into the VIP is through the toilet opening in the top slab; other than through this hole, no ash can be added or extracted from the pit, except when in the form of soluble salt being transported via groundwater. Assuming the quantity of soluble salt being transported is negligible compared to the insoluble ash components, ash is considered a conserved quantity throughout the pit. This assumption was not tested and is not based on any data or previous results. The faecal ratio of soluble salt to insoluble ash could support this assumption if investigated in future work.

The y-axis error bars do not show on the graph due to their height being shorter than the symbols used. The x-axis error bars are an estimate of the sampling technique accuracy as discussed in Section 4.1.2 Sampling.

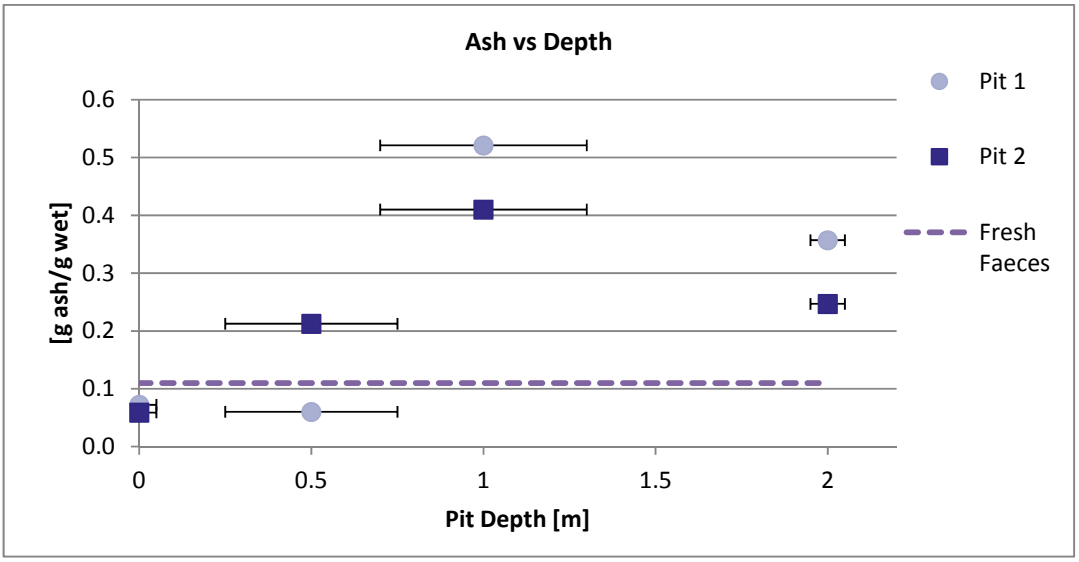

Figure 5.4: Point ash concentrations at 4 sample depths in Pit 1 (a) and Pit 2 (b) with the dotted line as the ash concentration of fresh faeces as reference.

As shown in Figure 5.4, both pits have a decrease in ash concentration from fresh faeces, at 0.11 g ash/g wet, to the top sampling point of the VIP, at 0.07 and 0.06 g ash/g wet for VIP 1 and VIP 2 respectively. There is a net increase in ash content on wet basis with increasing depth which is consistent with a decrease in organics and/or moisture. Faeces collected separately from urine is expected to have a higher ratio of ash than faeces and urine collectively in units of g ash to g wet sample due to the additional mass of moisture from the urine without a significant addition of ash.

The general increasing trend with depth indicates that ash becomes a relatively larger portion of the total mass with depth. Recall that depth is associated with the age of the sample in that as we move down the pit, the samples are older and have been subject to pit conditions longer. Variation could be caused by sampling inconsistency and lack of homogeneity in the pit or some of the assumptions of the analysis not being completely valid, such as a constant feed input rate.

5.3.2 pH

Before examining each analyte on a g ash basis, the unit-less measurements of pH for each sample is shown in Figure 5.5 for both VIPs. Pit 1 has noticeably lower pH values compared to Pit 2. Despite the opposite trends in the pits, the pH value at the bottom of both measured approximately the same, at 7.7. The pH value is likely to be strongly affected by groundwater hardness and alkalinity, especially measurements at the bottom of the pit.

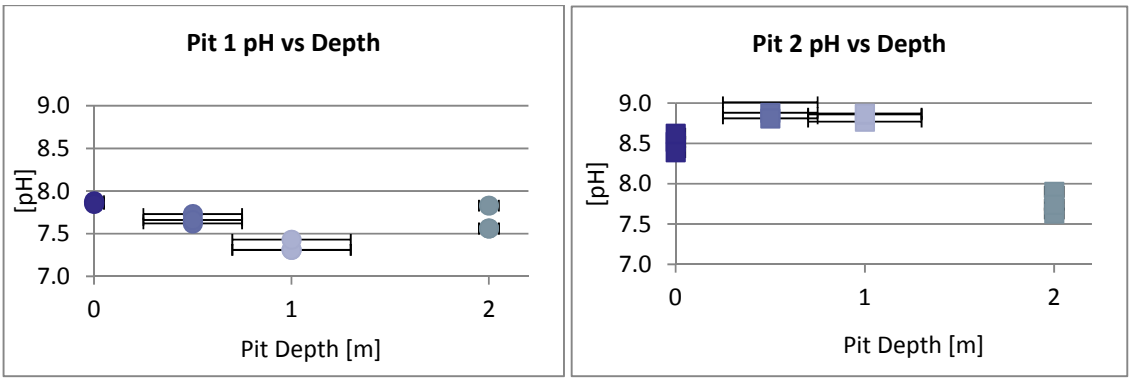

Figure 5.5: The triplicate point sample measurements of pH for VIP 1(a) and VIP2 (b).

Normal urine is slightly acidic with a pH around 6. Healthy people can have the pH range from 4.8 to 8.4 depending on their habits such as diet and exercise. The normal pH of faeces is also 6 but varies between 4.6 and 8.4 (Fritsch 1990). The expected pH of fresh urine combined excreta would be near 6. The pH data from the pit have are higher than the literature values for raw excreta.

5.3.3 Alkalinity

The alkalinity in both VIPs has a decreasing trend (Figure 5.6). The majority of the decrease occurs in the top 1 m of material. The ratio of alkalinity to ash stabilised after 1 m down the pit around .090 mg-$CaCO_3$/g-ash for Pit 1 and .097 mg-$CaCO_3$/g-ash for Pit 2. The overall decreasing relationship of alkalinity/ash with depth is similar for both VIPs.

The difference between replicate measurements for alkalinity was 1 mg/g and therefore may not show across the markers in the plot below.

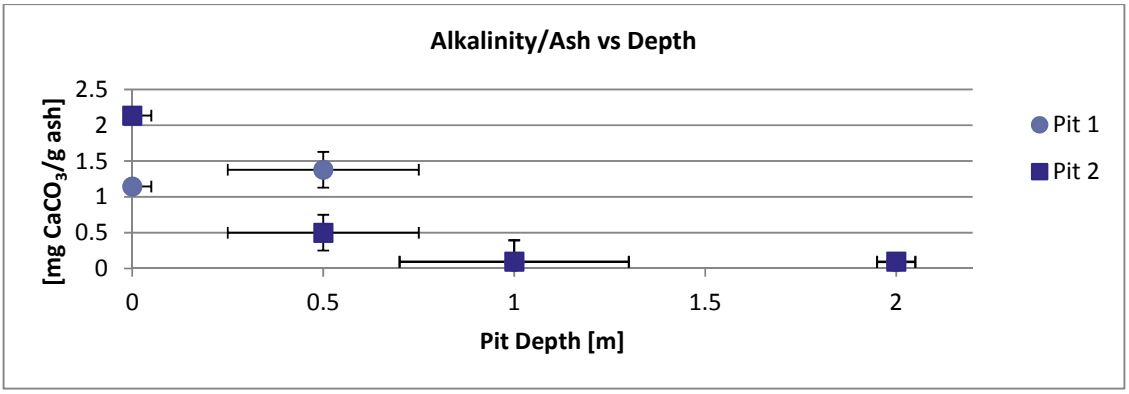

Figure 5.6: Point measurements for alkalinity concentration for VIP 1 and VIP 2.

Alkalinity can increase during aerobic processes when excess ammonia reacts with CO_2 produced by biological activity and results in bicarbonate. Additionally the excess ammonia can inhibit the bacteria that produce VFA leaving the existing volatile acids to biodegrade to H_2O and CO_2. Alkalinity can decrease due to micro-organisms initially converting urea to ammonia (Eckenfelder et al. 1995; Sterling et al. 2001). Because alkalinity is highly soluble, it can also be transported from the pit via groundwater. The local groundwater has a much lower alkalinity than the excrement entering the pit and, in the location of the studied pits, it is possible for groundwater levels to reach the pit. It is anticipated that the lowest level alkalinities are influenced by groundwater conditions, and that this would be the main reason why the two pits, located in the same geographic area, exhibited similar alkalinity to ash ratios.

5.3.4 COD

The COD of fresh faeces is 320 mg/g wet sample (Nwaneri 2009). Taking the measured moisture and ash content, the COD concentration is calculated to be 12 592.4 mg COD/ g ash. This COD concentration was taken from one study performed in the same region but on a limited sample of people whose diets most likely differed from that of the average pit user. However, this measurement is the best available for fresh faeces and will be used for comparisons here within. The top layer of the VIP content had a COD less than three times that of Nwaneri's value. This suggests that a significant portion of COD degrades quickly in aerobic conditions at the pit surface. The average value for a fraction of particulate COD increases from about 85% to 95% moving down the four point samples in the pit. The figure below shows the fractionated COD plot of particulate, soluble and total COD. According to a previous study on urine diversion toilets, the moisture content and COD concentrations have parallel trends (Buckley et al. 2008b). By comparing the previous moisture concentration plot Figure 5.3 and Figure 5.7, the correlation between moisture and COD concentrations is not very strong in a VIP. Although both show a

primarily decreasing trend, VIPs have many more mechanisms influencing the moisture content than sealed UD toilets. Figure 5.8 and 5.9 show the particulate and soluble COD fractions at each sample relative to the measured fraction of fresh faeces. All the fractions concentrations in the pit were much less than the fresh faeces' concentrations.

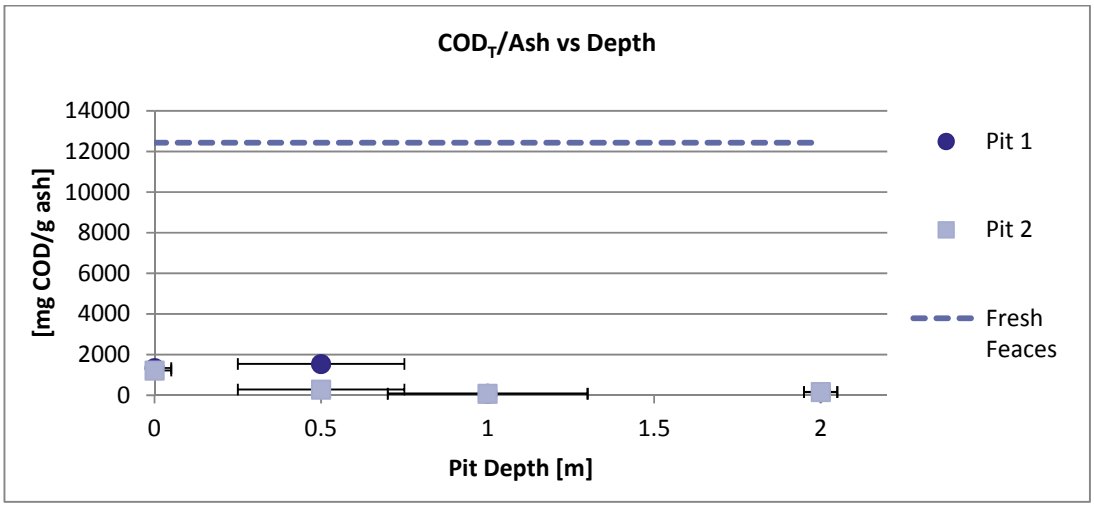

Figure 5.7: CODtotal point samples for VIPs 1 and 2 with fresh faeces data point for comparison

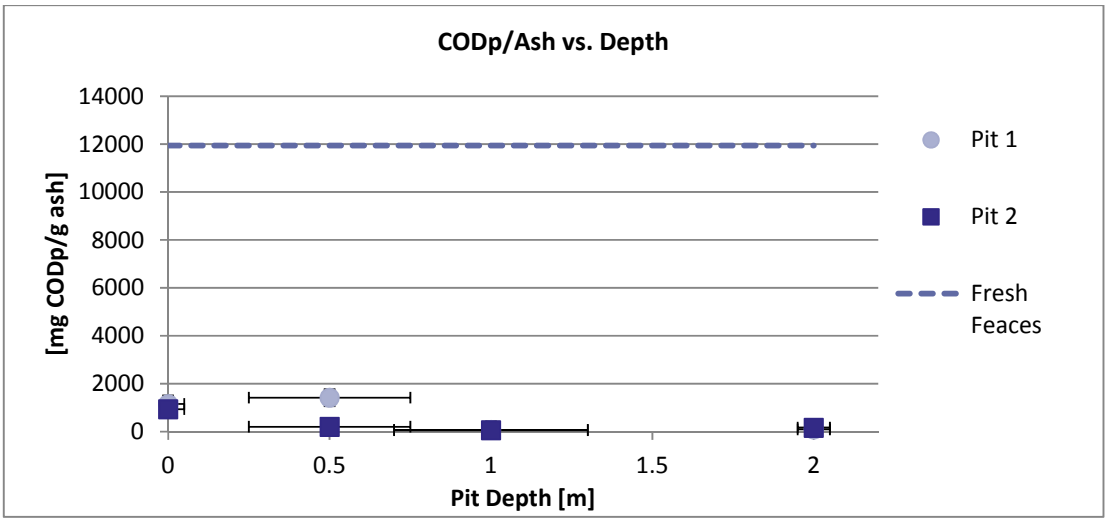

Figure 5.8: CODparticulate point samples for VIPs 1 and 2 with fresh faeces data point for comparison

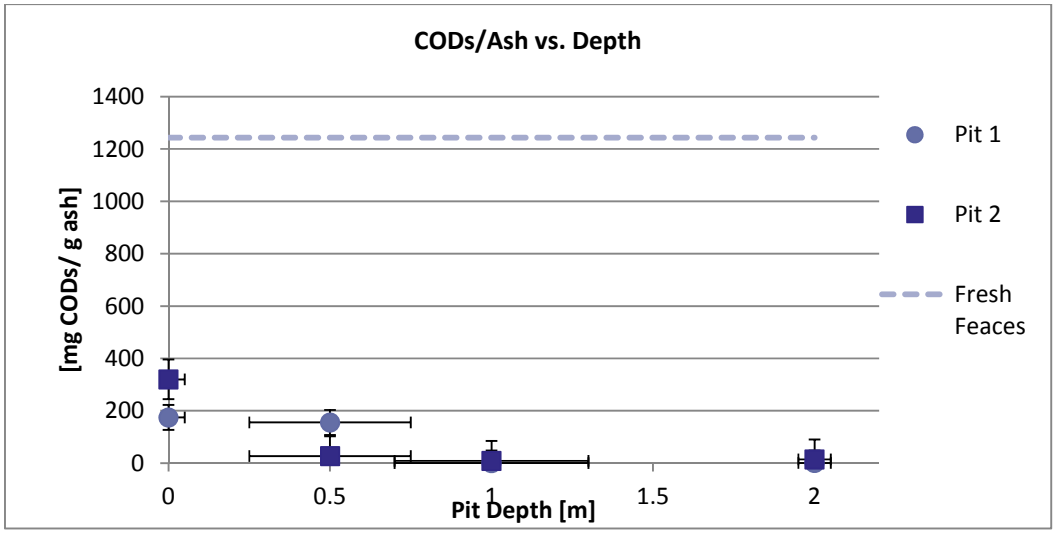

Figure 5.9: CODsoluble point samples for VIPs 1 and 2 with fresh faeces data point for comparison

Figures 5.10 and 5.11 show the measured total COD in each pit and compare it with the sum of the measured soluble and measured particulate COD fractions. The calculated and measured total COD points are very similar which validates the methods used for COD analysis.

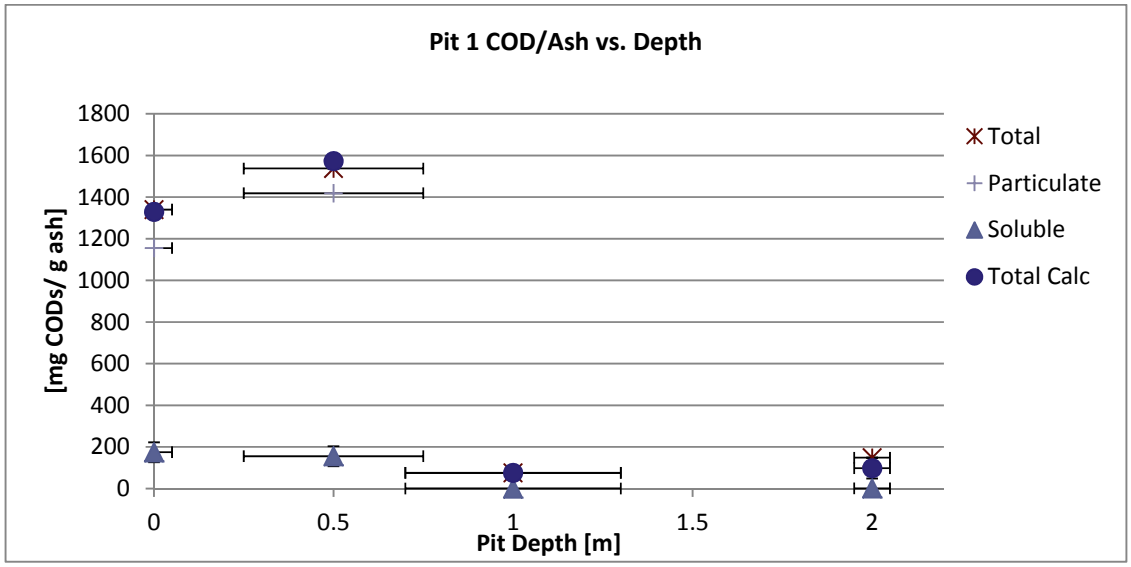

Figure 5.10: Plot of fractionated COD (Total, Soluble, and Particulate) components to compare to the total value for Pit 1.

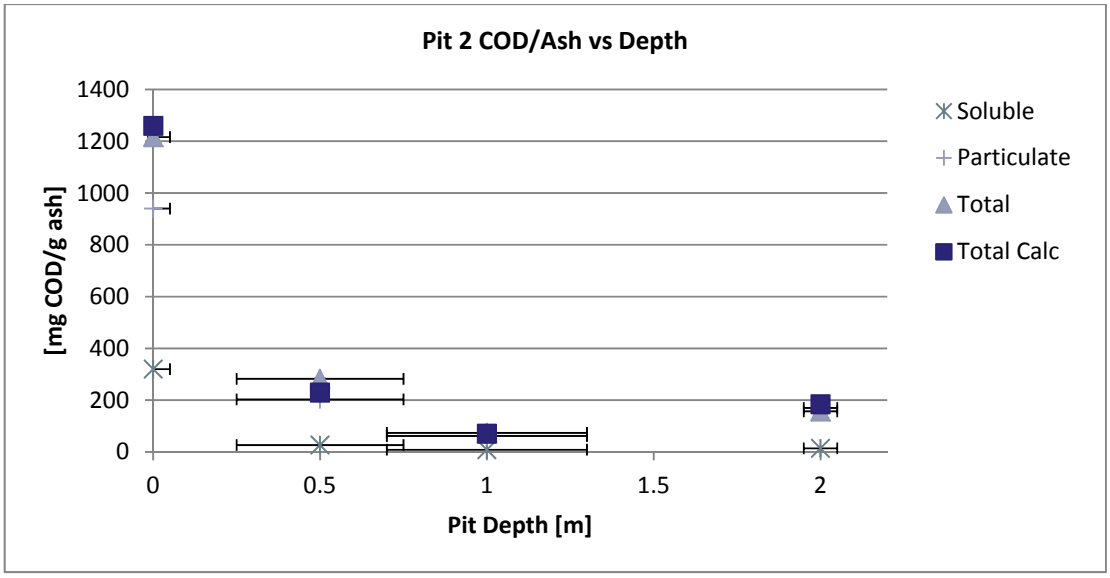

Figure 5.11: Plot of fractionated COD (Total, Soluble, and Particulate) components to compare to the total value for Pit 2.

5.3.5 Biodegradable COD

Total biodegradable COD (COD_b) as well as particulate and soluble biodegradable COD (COD_{sb}, COD_{pb}) was tested in VIP 1, with methodology details in Section 4.1.4.4. The method used for the biodegradability of COD is a 2 week aerobic experiment where the results determine the quantity biodegradable in a 2 week period. This method was used and the results are shown in Figure 5.12 and 5.13. Figure 5.12 shows the COD fractionation results of the COD_b. The COD_b of fresh faeces taken from Nwaneri 2009 is 256 mg/g wet sample which is over four times that of the measure COD of the surface contents in the VIP. In other words, about 22% of the COD_b of fresh faeces remained when the samples were taken off the surface of the VIP. The figure below plots the measured COD_p added to the measured COD_s with measured COD_t. The sum of the measured soluble and particulate COD is approximately equivalent to the measured total COD which validates the methods used for biodegradable COD analysis. These results also indicate that significant biodegradation has occurred with time. As before, this value is probably not universally valid due to the small sample basis and diet range.

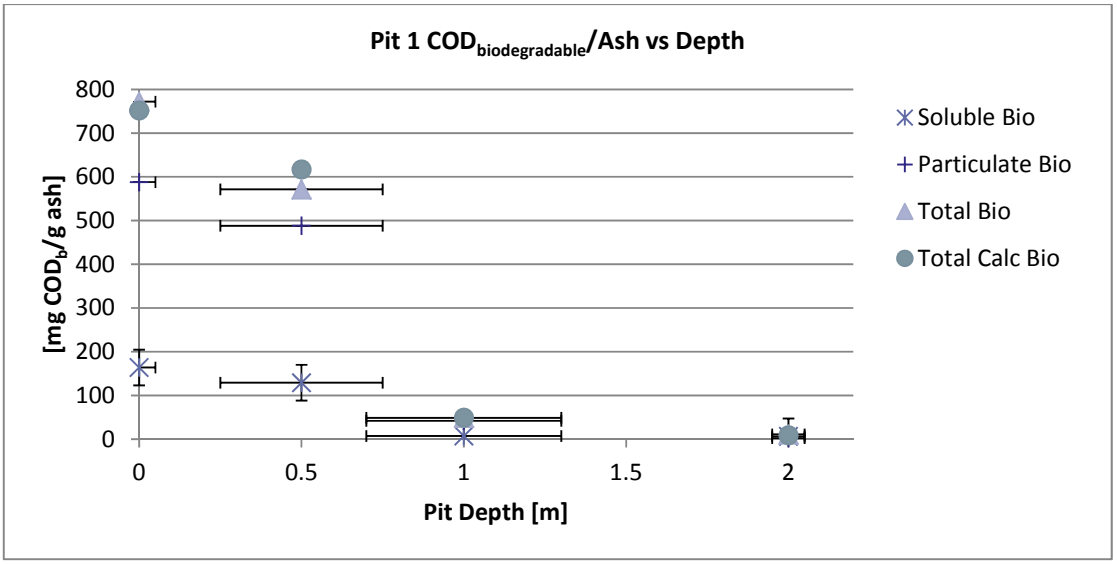

Figure 5.12: Biodegradable COD fractions/Ash point samples for Pit 1 with measured and calculated total biodegradable COD

Figure 5.13 shows the relationship of biodegradable COD fractions to total COD fractions. The majority of total COD and biodegradable COD is particulate matter and the majority of soluble COD is biodegradable.

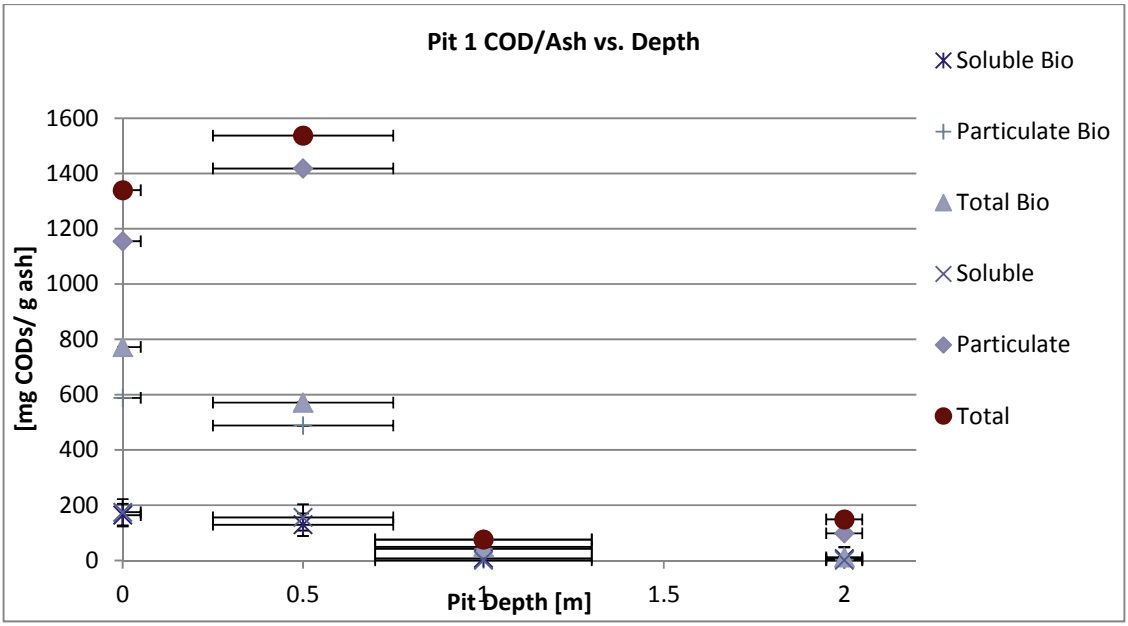

Figure 5.13: Total COD fractions/Ash point samples for Pit 1 and biodegradable COD fractions

5.3.6 Nitrogen

Total Kjeldahl Nitrogen (TKN) and ammonium (NH_4^+) were tested. TKN is the measure of ammonia and organic N. Total nitrogen includes nitrite (NO_2^-) and nitrate (NO_3^-). NO_2^- quickly

oxidizes to NO_3^-; however, neither NO_3^- nor NO_2^- are reported in fresh faeces by other works (Jönsson et al. 2004; Chaggu et al. 2007; Nwaneri 2009). Therefore TKN represents the total nitrogen present in VIPs. NO_2^- and NO_3^- are generated by aerobic conditions and because the bulk of the pit is anaerobic, they are not commonly present. However NO_2^- and NO_3^- are constituents of concern and are considered contaminants in drinking water. Pit latrines leach NH_3 which then oxidises in the vadose zone of the surrounding soil. This study does not look outside the pit boundary; however VIPs may be a potential cause of NO_2^- and NO_3^- found in the groundwater which may result in contaminated drinking water and should be considered when locating VIPs.

The total nitrogen in fresh faeces is 13.93 mg N/g wet sample (Nwaneri 2009). As before, the fresh faeces values are from a limited sample size and the general applicability to pit users is untested. Using the moisture and ash content, the total nitrogen in the fresh faeces samples is calculated to be 127 mg-N/g ash. In Figure 5.14, the fresh faeces nitrogen measurement is similar to that of Pit 2 taken at the surface of the VIP and nearly double of the measurement taken on the surface of Pit 1. However, this spread is probably not meaningful because nitrogen originates from protein which is a quantity that may differ significantly between the diets of fresh faeces sampled and the pit users.

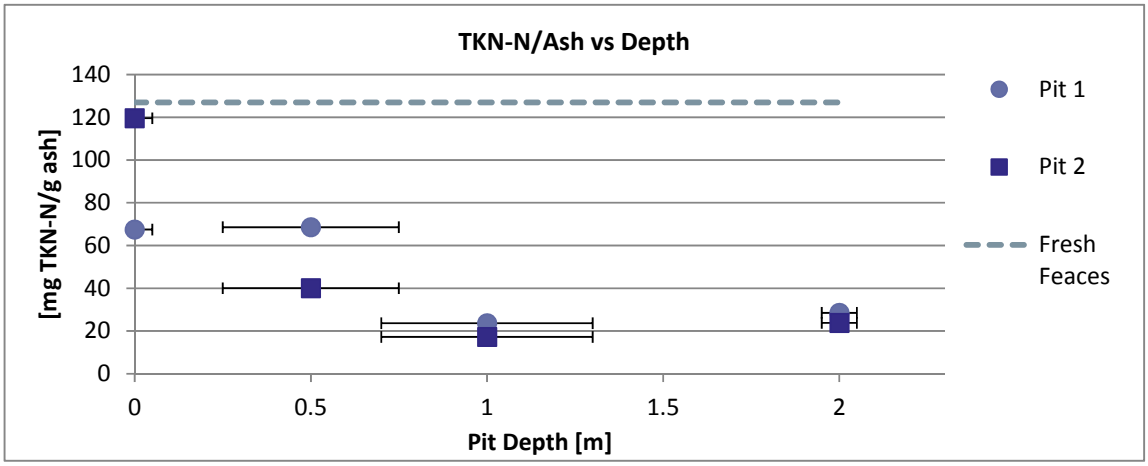

Figure 5.14: TKN at point samples in Pit 1 and 2 with total nitrogen of fresh faeces for reference

The ammonium and TKN data are plotted in Figure 5.15. There is no apparent correlation between changes in TKN values for each sample and changes in ammonium values. The ammonium fraction of TKN decreases, moving down the pit layers despite the fluctuations of TKN.

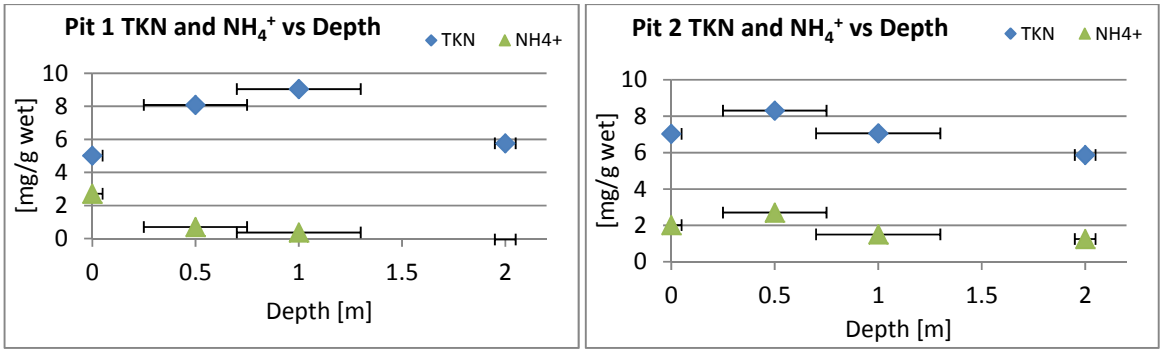

Figure 5.15: The point measurements for ammonia and TKN where the value between the points represents the organic nitrogen.

Analysis for NH_3 and NH_4^+, also known as free and saline ammonia (FSA), was performed, in addition to TKN. The difference between TKN and FSA concentrations is the organic nitrogen concentration and is interpreted in the figure as the vertical distance between the two data points.

When proteins degrade, organic N is converted into FSA, resulting in no net change in TKN. Any reduction of TKN could be due to the washout of FSA, which is highly soluble, transported in groundwater.

5.3.7 Phosphorous

The samples were analysed for total phosphorous and orthophosphate. Figure 5.16 shows the slight and steady decrease in total phosphorous concentration. The total phosphorous of fresh faeces is shown for comparison (Nwaneri 2009). However, the VIP sample likely includes, in addition to faeces, a combination substances including urine, which has a significant phosphorous content.

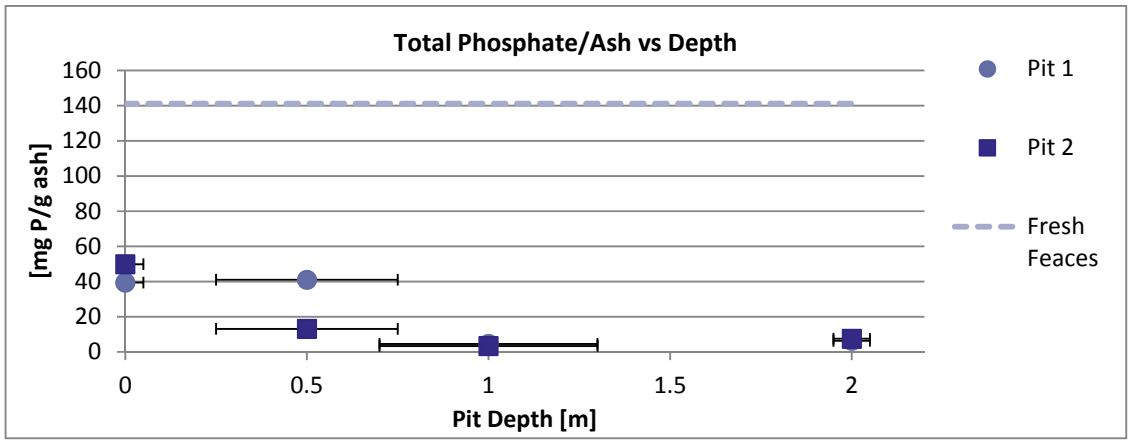

Figure 5.16: The point sample concentrations of total phosphorous for VIP 1 and VIP 2.

The point sample concentrations for orthophosphate, shown below in Figure 5.17, change similarly at each depth as total phosphorous, shown in Figure 5.16.

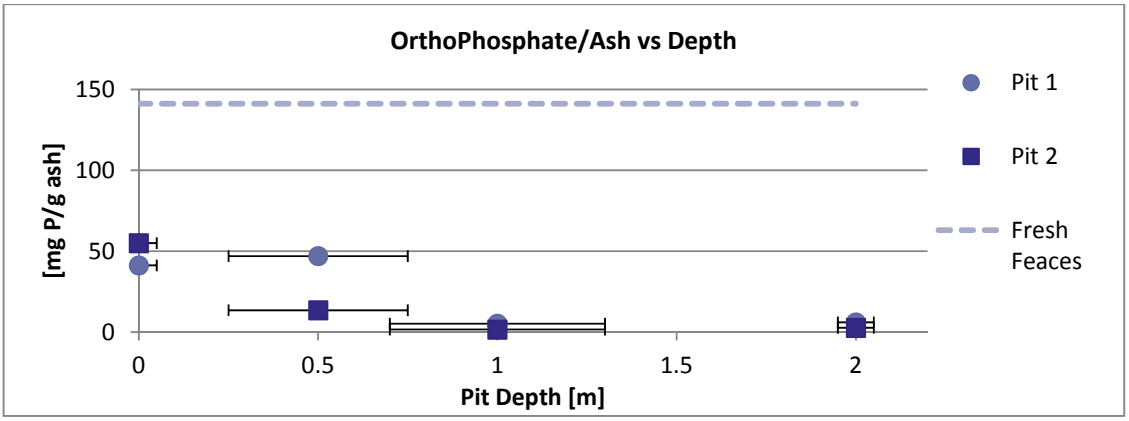

Figure 5.17: The point sample concentrations of orthophosphate vs. depth for VIP 1 and VIP 2

Total phosphorous is the sum of organically bound phosphate (OBP) and orthophosphate, a soluble fraction. In some samples, the orthophosphate concentrations were measured to be greater than the total phosphate concentrations. This indicates that most, if not all, of the phosphate is present in a form that reports as orthophosphate and there is either a significant unmeasured variance in the replicate analysis or a systematic interference in the initial digestion step for total phosphate that results in a systematically low measurement of total phosphate. OBP slowly reverts to orthophosphate through hydrolysis when organics break down in aqueous solutions therefore it is likely that phosphates are found in their soluble form in anaerobic conditions (Crites and Tchobanoglous 1998). If the contribution of leaching is not significant, the older the sample, the higher the ratio of orthophosphate to total phosphate in a sample. However this ratio may also be influenced by moisture content, temperature and any other factor that influence the rate of degradation of the organic material in the pit. As with other soluble components, orthophosphates are going to be transported with water movement and may be influenced by phosphates in groundwater. The concentration of phosphates in the groundwater near Savana Park is expected to be low. Leaching via this groundwater would cause a net movement of phosphate out of the pit. Phosphorous may also bind to iron in the soil, which would contribute to the formation of insoluble phosphorous compounds precipitates (Perrow and Davy 2002). This would explain any constant phosphorous presence not captured in the orthophosphate fraction.

Assuming that ash is conserved within the pit, it appears that phosphorous, total solids and COD have a decreasing trend with pit depth. Water, nitrogen and alkalinity are not showing to be strongly correlated with depth in the two sampled pits. The pit content does stabilise but the rate depends on the movement of groundwater (Dhaar and Robbani 2008) . The data from a study of VIPs in the eThekwini Municipality show that in most cases between 1 and 1.5 m deep, the percentage of biodegradability in the pit content has the most dramatic decrease, dropping below

20 percent (Bakare et al. July 2012). Due to the nature of pit latrines, variation in feed material and the inherent uncertainties in the measurements, the data contain a lot of noise.

5.4 Volume Reduction Analysis

The following data analysis investigates the depth-age relationship of pit content and any significance it has on the filling rates for VIPs.

Figure 5.18 illustrates where point samples are taken and where pit layers are designated.

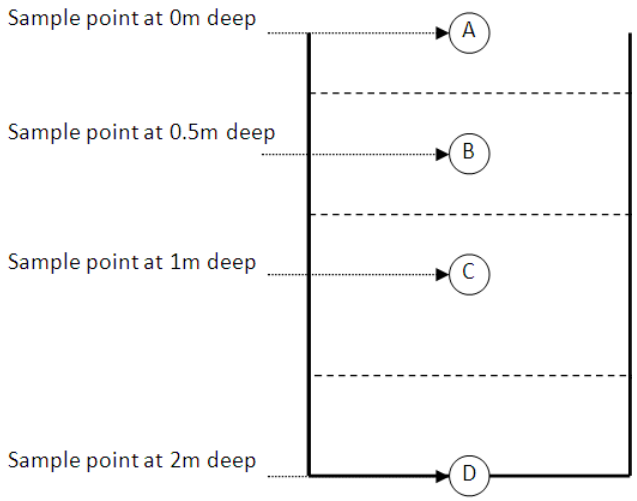

Figure 5.18: Diagram of point samples and layers

5.4.1 Age-Depth Relationship

In the following figures, the value at each layer represents the equivalent volume of fresh faeces that would occupy that space if no compression or degradation took place. In Figure 5.19, the ash concentration of the sample taken from the reported level in the pit has been used to calculate the original volume (pit input material) that would result in 1 m^3 of pit sludge at the sample level, assuming that the ash is non-reactive and conserved, and thus that the increase in ash concentration is directly due to a decrease in total volume. Integrating the measured values of ash across the depth results in the estimated total ash concentration for that volume. Fresh faeces, the top bar in the diagram, is shown as the unit measurement of 1 m^3 for comparison. Layer 1, from 0 m to 0.5 m, Pit 1 is the only layer that had a lower ash concentration than fresh faeces. This could be due to variances in the sampling, increased moisture content in that layer or different feed characteristics at the time in which the material was deposited. Grams of ash per gram wet sample and total solids are found according to the method in Section 4.1.4.1.A sample calculation for the conversion to ash basis is found in Appendix II. The g ash/g dry sample values are integrated across the pit depth and

divided by the g ash/ g dry ratio for fresh faeces. These values are plotted below to show the volume relationship per layer relative to the ash concentration.

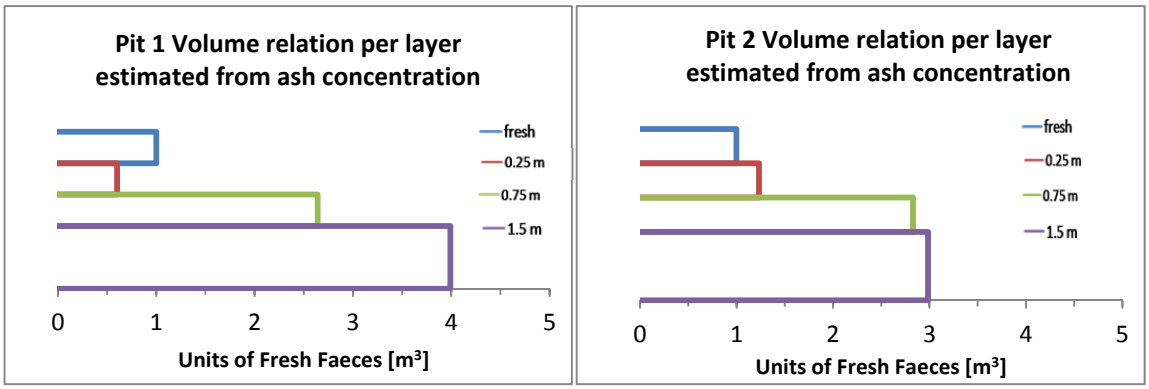

Figure 5.19: Volume equivalents of fresh faeces present in each layer determined from ash fraction

The concentration of ash in the bottom layer of Pit 1 is approximately 4 times greater than that of fresh faeces. The data imply that Pit 2 has a volume reduction of 3 to 1 from fresh faeces to the degraded, compressed contents at the pit base. Therefore if the content consisted of only human excreta, the incoming material would be one quarter to one third of the initial volume by the time it reached the bottom of the pit due to the pit mechanisms. In other words, a pit can hold 3 to 4 times its volume of fresh faeces assuming the ash concentration sampled is an approximate representation of the material at that depth across the pit.

Figure 5.20 estimates the total amount of ash in each of the three layers defined in Figure 5.18. These estimates were obtained by averaging the values of the samples taken at the top and bottom points that define the layer. It is a simplification to assume that this average is representative of the true average ash composition in the layer, however the analysis nevertheless provides an insight into the probable distribution within the pit. The quantity of ash mass per layer increases with depth as shown in the figures below. The majority of the ash remaining in the VIP is contained in the bottom layer.

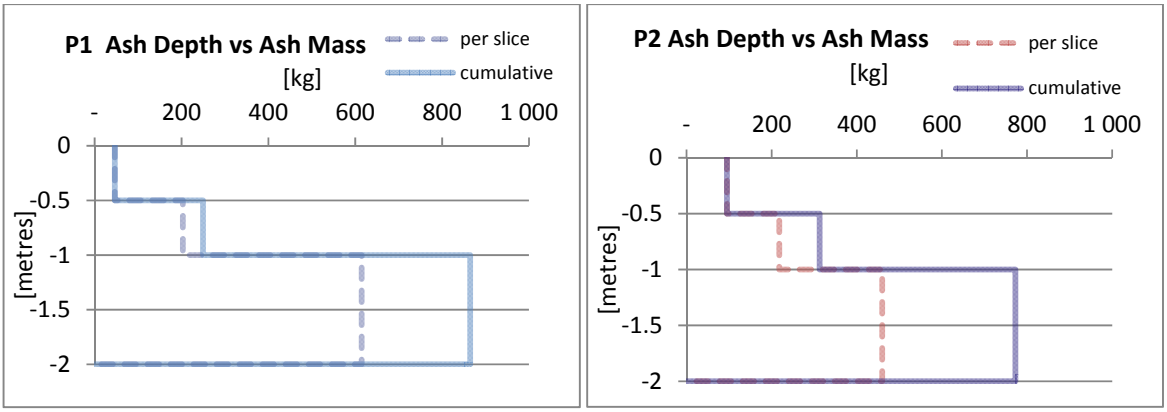

Figure 5.20: Depth of pit layer vs. mass of ash per layer and accumulative for VIP 1 (a) and VIP 2 (b).

The approximate age of the material in each layer can be determined based on the per capita production of faeces per year taken from (Jönsson et al. 2004). As reported by the community liaison officers, the best information available implies that the VIPs were used relatively consistently by 7 users from installation to emptying. It is assumed that each person produced an average of 51 kg of faeces per year and the average ash content of fresh faeces is 0.11 g ash/g wet (Nwaneri 2009).

The proportion of the ash mass in each layer to the total ash in the pit is found. These calculations can be found in Appendix II.

The mass of fresh faeces deposited is approximated and used to estimate the equivalent years per mass of ash in the pit. With the approximate equivalent number of ash years and the ash mass calculated, the ratio of ash in each layer to the sum of ash in the pit can be used to find the approximate age of each layer in the pit assuming only faeces had been deposited.

By multiplying the faecal rate of input rate (0.255 m/ year-calculated by the assumed density of the sludge, the measured area of the pit, the average faecal production rate from the literature and the reported number of people using the studied VIP) by the equivalent years, the approximate depth of the pit can be found. By comparing this depth with the depth value around which the ash concentrations were integrated, the total compaction through dehydration and biological and chemical processes can be estimated.

Taking the age of each layer inferred from the previous steps and multiplying by the pit depth faecal build-up and the equivalent rubbish input rate (10% of total pit input), the equivalent depth of rubbish per layer can be calculated. The rubbish mass in each layer is calculated by multiplying the assumed average rubbish density (1 300 kg/m^3) and pit cross-sectional area (1.4 m^2). These calculations are shown in Appendix II.

Subtracting the rubbish depth in each layer from the total depth of each layer and multiplying by the inferred ash concentration of excreta in that layer, the ash mass of that layer can be recalculated, displacing the volume used by rubbish. With a new cumulative faecal ash mass, the same calculations can be done as before to find the equivalent years the pit has been in use when taking into consideration rubbish volumes.

Using the same calculation as before, the approximate age of each layer can be inferred by using the ash mass in that layer and the cumulative ash mass and the years of pit use.

Table 5.2 includes the mass of ash in each layer as well as the age of the contents in that layer with rubbish volumes of approximately 25% based on literature and observation values taken into account. It shows that VIP 1 and VIP 2 have been in use for roughly 14.5 years. These calculations can be found in Appendix II.

Table 5.2: Ash mass, age and percent total mass of contents in each pit layer for VIP 1 and 2

	VIP 1			VIP 2		
Layer	**Depth [metre]**	**Ash per slice [kg]**	**Time per slice [years]**	**Depth [metre]**	**Ash per slice [kg]**	**Time per slice [years]**
1	0 to 0.5	44	0.78	0 to 0.5	84	1.79
2	0.5 to 1.0	150	3.44	0.5 to 1.0	160	4.10
3	1.0 to 2.0	380	10.38	1.0 to 2.0	330	8.65
Total	0 to 2.0	574	14.60	0 to 2.0	574	14.54

The VIPs in Savana Park were constructed and in use by 1996 (Moodley 2010). The pits were in use for 14 years before the samples were taken in 2010. This coincides well with the calculated cumulative age of the pit material given the estimations and approximations involved. A measured fill rate is not known because the VIP content was buried on-site in a pit adjacent to the VIP vault as the pit was being emptied. The calculated fill rate is based on the measured distance from the top of the excreta pile to the top of the vault and the measured dimensions of the vault. The slope of the content was not known but was observed to be nearly flat given these pits were nearly full.

The pit fill rate was estimated for the content material under three conditions. The pit content height over time is shown in Figure 5.21 and 5.22 for the three compositions:

- only fresh faeces throughout the pit

- assuming excreta volume addition at 51 kg/year/person, no solid waste and no volume reduction

- only excreta at various levels of degradation and stabilisation
  - assuming excreta volume addition at 51 kg/year/person, excreta volume reduction at each depth from the previous compaction calculations and no solid waste

- excreta at various levels of degradation and stabilisation and proportional quantities of rubbish
  - assuming excreta volume addition at 51 kg/year/person, excreta volume reduction at each depth from the previous compaction calculations and solid waste as ¼ the volume of pit contents at the end of filling

These heights are based on the measurements of the VIPs used in the study with a cross-section of 1 m × 1.4 m. The height of the content in the pit rises the quickest when no compaction, degradation or volume reduction due to leaching is considered for the material deposited. The excreta are measured as if unchanged over time and new excreta are piled on top of previous deposits. The circumstance in which the content height rises the slowest is when the material in the pit is purely excreta that degrade over time. With degrading excreta and no rubbish, the pit fills the slowest. The quickest rate prediction for both pits, degrading faeces and rubbish, is around at 0.25 m/year while the slowest rate for both pits, degrading faeces with no rubbish, is about 0.06 m/year.

The filling qualities found in the VIPs in this study are ones in which the excreta degrade over time but unbiodegradable rubbish is present in the pit. The calculated average pit filling rate given the cross-sectional area of these pits is 0.14 m/year. The fill rate for this condition is between the nondegrading excreta and the degrading excreta. From Figure 5.21 and 5.22, the measured conditions are closer to the heights calculated with degrading excreta with rubbish. However, if rubbish were absent and the VIPs were properly used, these predictions indicate the pit could take an additional 10 years to fill assuming a pit height of 2 metres. Still, 2002 estimated that with a linear fill rate the pits would last about 7 years. That estimation corresponds well to the fill rate without degradation, crossing the pit height 2 m line at the 7 year mark.

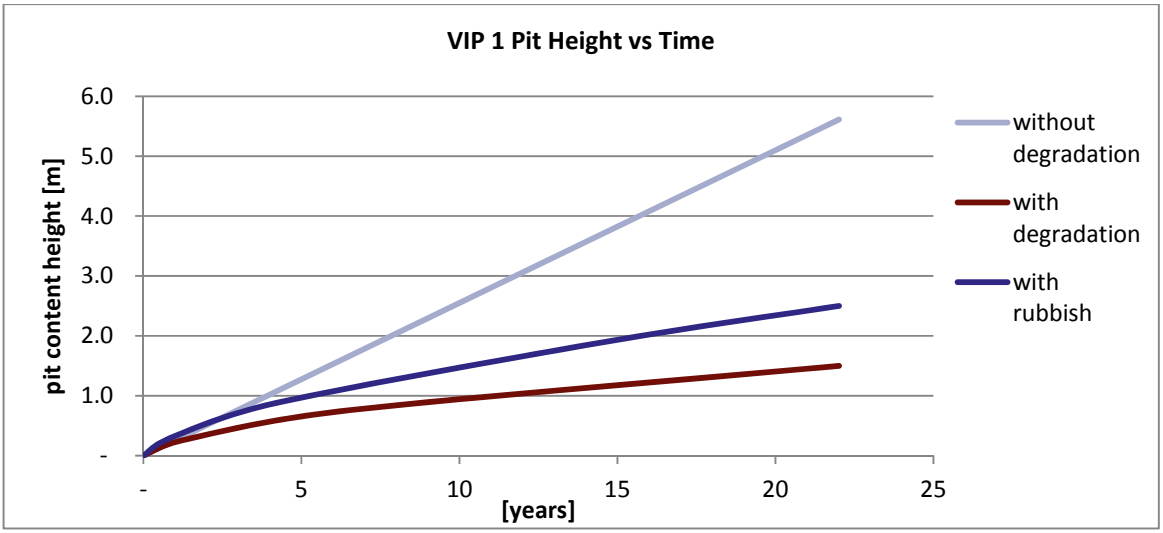

Figure 5.21: The height of the pit contents under conditions of the contents not degrading, the contents degrading, and considering rubbish with excreta degradation for VIP 1 vs. time since beginning of pit use.

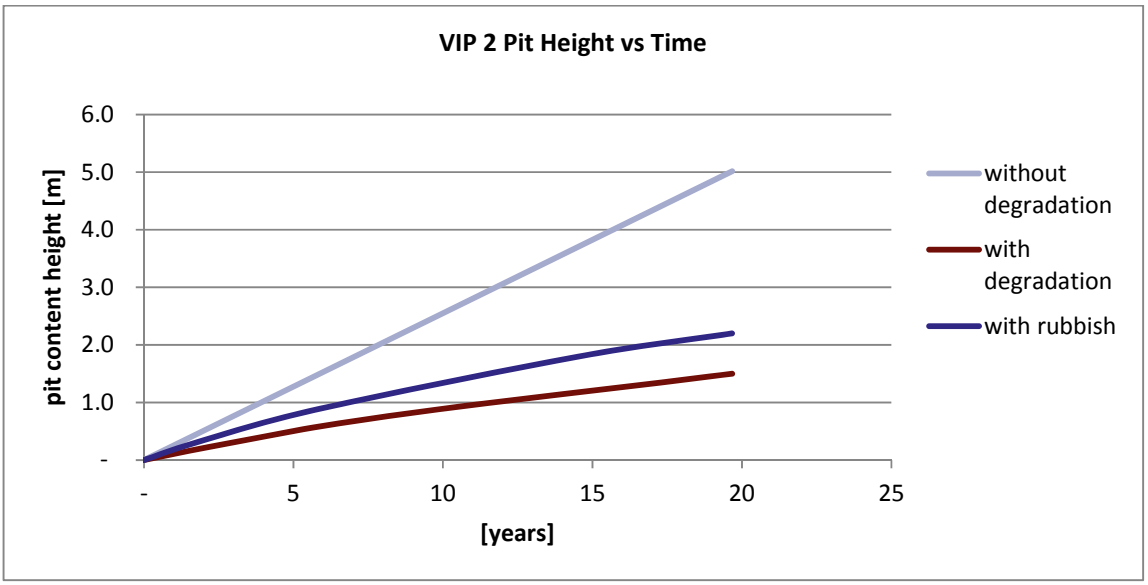

Figure 5.22: The height of the pit contents under conditions of the contents not degrading, the contents degrading, and considering rubbish with excreta degradation for VIP 2 vs. time since beginning of pit use.

The calculated rates of degradation, and compaction/ volume reduction due to leaching are similar for both VIPs. The rate of degradation in VIP 1 is approximately 0.37 m^3 a year and VIP 2 is approximately 0.42 m^3 a year. The volume degraded each year corresponds to the difference in height of pit content if the faeces underwent no degradation and the actual height of the pit content. To illustrate this point, it can be calculated that the content in a pit with the same cross-sectional area would be approximately 4 m higher after 22 years without degrading than the actual height of the pit content as shown in Figure 5.23. The points were calculated by examining the estimated

excreta input. This volume was based on the ash concentration at a layer and the ash concentration of fresh faeces. The volume of the matter in the pit is compared to the calculated volume of the pit content assuming the entire layer was composed of excreta exclusively. The volume of rubbish was not considered in Figure 5.23 in order to represent the potential rate of degradation in a properly used VIP containing only excrement.

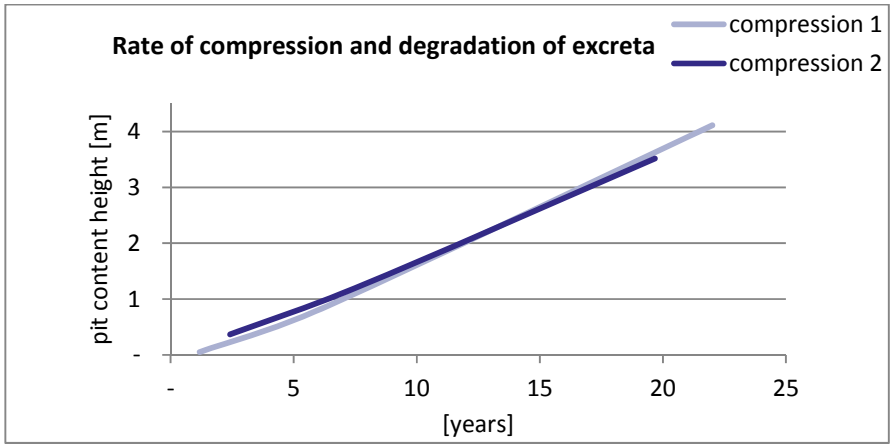

Figure 5.23: Excreta content compression over time calculated from pit input and actual height without considering rubbish input.

The ratio of household solid waste to excreta increases with depth. As the excreta degrade, compress and dehydrate, the non-faecal matter does so at a slower rate, if at all. The rubbish is transferred down the pit due to older excreta volumes decreasing and newer excreta accumulating on top. The rubbish content decreases available volume from the pit by existing as a permanent unbiodegradable presence which in essence decreases the years of use before emptying is necessary.

Using the standard numbers, 51 l/p/yr and 7 people per latrine over 14 years produces about 500 l of faeces. Adding the 10% rubbish input rate produces 5.5 m^3 of material which resulted in 2.8 m^3 in the pit at the end of the 14 years. This is a volume reduction of about 51%. The analysis earlier in this section using only ash concentrations showed a 75% and 67% volume reduction. The increased reduction can be attributed to not including the non-degradable rubbish. Using the cumulative ash values from Figure 5.2 to back out the input rate yields 74 l/p/y. This is greater than the standard value used of 51 l/p/y. The 51 l/p/y is only accounting for production of excreta. Aside from the assumptions, this variation may be from ash deposited in the pit from non-user excreta sources or through soluble ash transported into the pit.

5.5 Model of Pit Filling Rate

Arising from the data obtained in this study, a model of pit filling rate was developed by Brouckaert, Foxon and Wood (submitted 2012) in which the volume of material in a pit was modelled as a function of time, faeces addition rate, degradation rate, rubbish-to-faeces addition ratio and generation of non-degradable residual from degradation of degradable constituents of the pit contents. The derivation and publication of this model post-dates the work presented in this study. However, it provides important insights into the application of this study. An equation was produced to model the volume of pit contents in a VIP latrine. A copy of the paper submitted for publication to Water SA is included in Appendix IV.

The model is only valid for degradable components and does not comment on the transportable components. A detailed model for transportable components could only produce significant results if known input values were available for all water sources and this kind of information is simply not available. The model makes use of a single biodegradation rate. Since concentrations of analytes in the feed to the pit are not known, the model uses the top layer composition as the feed composition; thus the degradation rate is essentially the anaerobic degradation rate and the aerobic degradation is not modelled (Brouckaert et al. submitted 2012). The model takes into account that a fraction of degraded excreta becomes unbiodegradable while the rest remains biodegradable.

The model uses continuous degradation of the material. The ratio of biodegradable to unbiodegradable can be altered to take into account variations in rubbish content.

5.5.1 Fill Rate Model

The following equation represents the volume available in the VIP.

$$V(T) = R_u \cdot \left[\left(1 + k \cdot \frac{v_{bo}}{v_{uo}} \right) T + \frac{\left((1-k)\frac{v_{bo}}{v_{uo}} \right)}{r} \left[1 - e^{-rT} \right] \right]$$

(Brouckaert et al. submitted 2012)

Where:

$\boldsymbol{R_u}$ = the rate of addition of unbiodegradable material at t [m^3/d]

$\boldsymbol{k}$ = volume ratio of new unbiodegradable from old biodegradable fraction [m^3/m^3]

Vbo/Vuo = initial volume of biodegradable material per volume of unbiodegradable material [m^3/m^3]

T = time since pit started filling in days

r = rate of degradation constant

Parameter Derivation:

$\mathbf{R_u}$: The rate of addition of unbiodegradable material at any time, t, is dynamic due to the fraction of biodegradable material changing. This rate, given in m^3/day, takes into account the original unbiodegradable portion of excreta as well as the addition of rubbish. These were found to be very similar at 0.00028 and 0.00027 m^3/day for the two VIPs examined in eThekwini by analysing the estimated rubbish content and the unbiodegradable COD from excrement.

k: When biodegradable substrate is biodegraded, a fraction becomes new cell material. A small fraction of this new cell material is unbiodegradable. Therefore a part of all biodegradable material ends up as unbiodegradable residue. The value found in the literature is that 8% of biodegradable material ends up as unbiodegradable residue on a mass basis under anaerobic conditions (IWA 2002). However the pit filling model uses a volume basis therefore this constant is converted to m^3 unbiodegradable organics generated/ m^3 organics biodegraded by using our assumed density of 1 g/ml.

$\mathbf{V_{bo}/V_{uo}}$: A fraction of every deposit into the pit is biodegradable. To model VIP volume, the ratio of the volume of biodegradable material to the volume of unbiodegradable material when it initially enters the pit is estimated based on the biodegradable fraction of fresh faeces and the inclusion of rubbish. Previous work has shown that faeces biodegrades between 80 and 90% within a timeframe of days to weeks in the presence of oxygen. The majority of the pit content continues to degrade for years. The VIPs are estimated to be 25% rubbish by volume when they are emptied. It was calculated that, assuming the depth time model is correct, rubbish enters the pit as 10% of the total input. Therefore 10% of the total input is unbiodegradable rubbish and of the remaining 90%, an additional 10% is the unbiodegradable organic and ash component. The ratio of material that will biodegrade during its lifetime in the pit was initially calculated at 81%. The initial V_{bo}/V_{uo} ratio used was 4:1 giving the 80% ratio. However, adjusting this ratio to empirically fit the data points, a ratio of 8:1 was found as the best fit. Approximately 89% of the input biodegrades while in the pit. Assuming the model and rubbish input rate is approximately correct, nearly all of the faecal input biodegrades over the pit's lifetime.

T: The amount of time the pit has been in use is necessary to determine the volume available. If the number of people using the pit changes or if the pit goes unused for a significant amount of time, the fill rate and degradation processes are altered. If the pit was emptied, it should be noted whether the emptying was complete or if there was a volume of material remaining in the pit. The two pits

examined in this study were each owned by one family for the duration of their use. They were used continuously without emptying since the VIPs were built in 1996. The VIPs were emptied in May 2010. Therefore the VIPs were in use for 14.5 years making T approximately 5 300 days in the model. t is the age of a particular layer of the pit, i.e. the number of days since the material in that layer was deposited. Therefore the t value for the bottom layer is t=T=5 300 d and t=0 on the top of the pit making t vary from 0 to 5 300 days.

r: The fraction of original material remaining at time t is given by e^{-rt}. The *r* in this equation is the rate of degradation. It is expected that many factors affect *r* including temperature and soil conditions but what these factors are and the extent to which they affect the rate of degradation is beyond the scope of this study. After entering the parameters into the model, *r* was adjusted to fit the measured data, defining *r* through calibration of the deterministic model. The parameter *r* was determined to be 0.006 and 0.009 for VIP 1 and VIP 2 respectively.

The estimated amount of rubbish removed from the sampled VIPs was observed at 25% of the pit volume. The capacity of the VIP as calculated from the measured dimensions is 1.4 m × 1 m cross-sectional area and 2 m deep for a total volume of 2.8 m^3. Approximately 0.56 m^3 is rubbish and 2.2 m^3 is faecal matter assuming the rubbish fraction is a quarter of the total excreta.

If rubbish enters the pit at 10% of the rate that faecal matter enters, the final percent of rubbish in the total pit volume is predicted to be 24%, due to the degrading and compaction of the excreta. These calculations are shown in Appendix II. The calculated fill rate of the pit is 0.36 m^3/year based on the average number of pit users and the average volume of excreta produced found in previous works, therefore the household solid waste fill rate is 0.04 m^3/year. Over the course of the VIP use which for this study is 14.5 years, the pit would have accumulated approximately 0.67 m^3 of unbiodegradable rubbish. Although the ratio of rubbish input to excreta input is assumed to be constant, the ratio of rubbish to excreta in the cumulative pit contents increases. The increasing ratio of rubbish per layer is because the household solids do not degrade as rapidly as excreta but instead continue down the pit as the excreta is degraded and compressed. As shown in Figure 5.24 and Figure 5.25 the models using an 8:1 ratio for V_{bo}/V_{uo} correspond well to the sampled data from the VIPs. The 8:1 ratio used in the model supports the previous calculation of rubbish entering the VIP at a proportion of 1 to 10 to that of faeces and including the fraction of faeces that is unbiodegradable.

All model parameters may vary in each VIP, however some vary more than others. Applying this model to VIPs in other soil types, cultures, user habits, climates, water table levels, and other

conditions would allow all the parameters to vary. It is expected that parameters *k* and *r* will vary relatively less than parameters relating to the feed rate and composition.

- The conversion of biodegraded material to unbiodegradable material, *k*, should remain relatively constant. Although the VIP content goes through aerobic and then anaerobic degradation, the model considers the process as one reaction. *k* in this case is taken as the average reaction. Because *k* relies on what fraction of the degradation occurs aerobically and what fraction anaerobically, the parameter will vary as the fill rate and moisture levels vary. Increasing the time the excreta spends in aerobic conditions will make *k* bigger. However, the difference in *k* between aerobic and anaerobic degradation is suspected to be undetectably small, which would therefore make *k* an approximate constant.
- The rate of degradation, *r*, should remain relatively constant as excreta should decay at a similar rate under similar conditions. However, differences in the excreta environment will affect the degradation rate. The variance in the fraction of time the material spends aerobically or anaerobically in the pit depends on the moisture content as well as the fill rate. Increasing the time the excreta spends in aerobic conditions is one condition that will make *r* larger.
- R_u and V_{bo}/V_{uo} are expected to vary more than the other parameters as they are more user behaviour dependent. The fraction and rate of unbiodegradable material depends on the user input into the VIP. There will be significantly less unbiodegradable material in the initial pit input if only excreta is deposited, however many users deposit rubbish as well. These parameters could change from family to family and even more from culture to culture. An increase in rubbish content would cause V_{bo}/V_{uo} to decrease and R_u to increase. The *T* parameter was known in this study from records kept by the eThekwini Municipality. However, often VIP construction date and use history is unknown. This is where more studies on VIPs where the usage history is known would be helpful to be able to estimate the age and user profiles of VIPs without records.

Using the ash concentration data and the estimated rubbish volume ratio from VIP 1, the fill rate for that particular VIP is graphed below. In Figure 5.24 the inferred fill rate based on the measurements is graphed along with the modelled fill rate. The model fill rate graphed below has a V_{bo}/V_{uo} of 8, *k* is 0.085, *r* is 0.006, R_u is 0.00028 and *T* is 5300 and where *r,* R_u, and V_{bo}/V_{uo} are found empirically for the best fit.

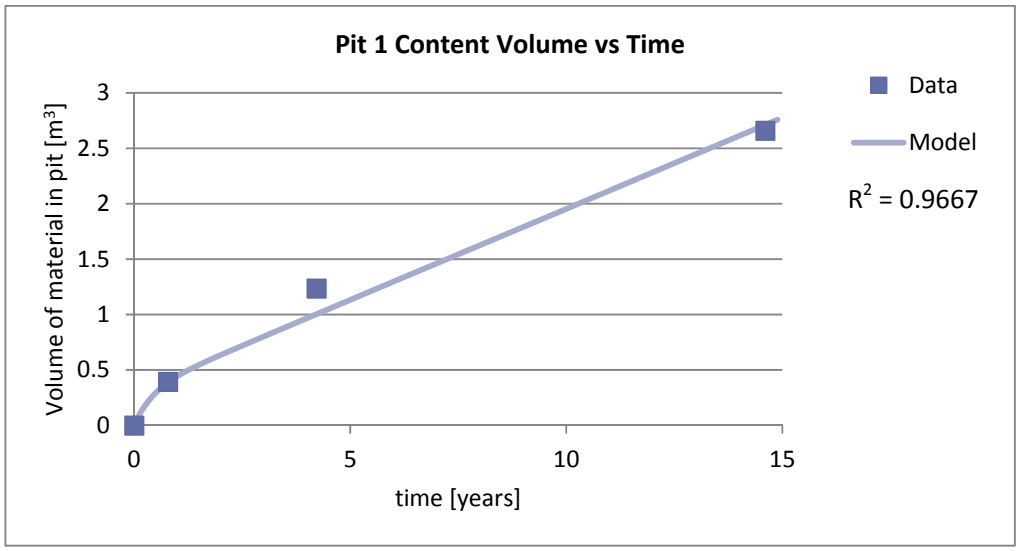

Figure 5.24: The fill rate from the model plotted against the fill rate from the data for VIP 1.

The fill rate for VIP 2 was plotted in the same way as VIP 1, using the ash concentration data at each level and the estimated rubbish volume for the pit. Figure 5.25 shows both the fill rate from the inferred data as well as that from the volume equation. The model fill rate graphed below has a V_{bo}/V_{uo} of 8, k is 0.085, r is 0.009, R_u is 0.00027 and T is 5300. Where r, R_u, and V_{bo}/V_{uo} were found empirically for the best fit.

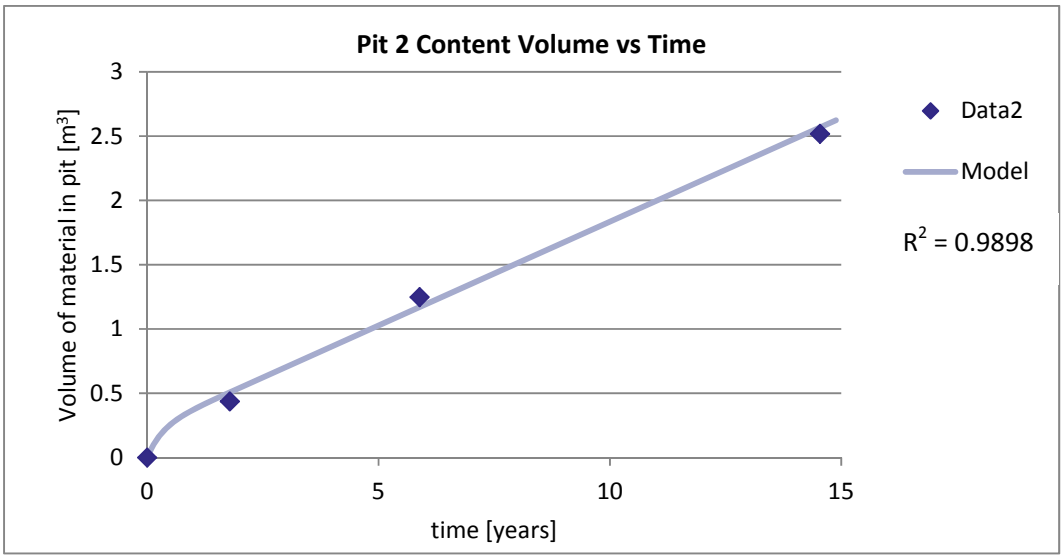

Figure 5.25: The fill rate from the model plotted against the fill rate from the data for VIP 2.

There are variations in the parameters in the equation to model the fill rates for VIP 1 and VIP 2. Ru varies slightly where VIP 1 is higher due to a higher input rate of unbiodegradable material.

Vbo/Vuo and k are the same for both models. Parameter r is lower for VIP 1. The range of explanations for slower degradation in VIP 1 include differences in moisture content, water transfer, temperature, and user variations. Further studies examining these effects would reveal a more detailed explanation to these results. However, given the variable nature of pit contents, the variable pit feed characteristics and rate, and the significant simplifying assumptions in the model (e.g. that the feed is constant in terms of composition and feed rate over the life of the pit), not too much can be inferred from the precise values of parameters used in these models.

6 Conclusion

Two similar VIPs were emptied and the content chemically analysed. Significant trends in some components were found. A fill rate model was formulated independently of the data. The model parameters were calculated such that the model described both sets of data well. This was only possible because the VIPs had similar characteristic. However, because two similar VIPs still varied in behaviour, it is apparent that many factors contribute to the characteristics of the content of a particular VIP. The parameters used in the model include a ratio of new unbiodegradable volume from old biodegradable volume and a constant for rate of degradation which is expected to vary based on the geographic and topographic location of the VIP, the user frequency, diet and habits, and the geometry of the pit vault.

There were two strong common traits of both VIPs: With time, a significant volume of excreta is no longer present in the pit through biological degradation, leaching of soluble components and dehydration. The elimination of household rubbish will significantly extend the lifetime of a VIP.

The ratio of household solid waste to excreta increases with depth. Excreta degrade, compress and dehydrate at a much faster rate than non-faecal matter. The rubbish is transferred down the pit increasing rubbish density at the bottom. The presence of rubbish reduces the pit volume and decreases the lifetime of the pit. Many components affect VIP performance; however reducing rubbish will have a significant impact on the pit lifetime. The rubbish content decreases available volume from the pit by existing as a permanent unbiodegradable presence which in essence decreases the years of use before emptying is necessary.

7 Recommendations

Increasing the sample number and pit variety would supplement the analysis in this study. Because the two VIPs analysed were similar in location, make, and user records, the data cannot be extrapolated to other sites or VIP types. However, by separately analysing similar VIPs, the data from each pit is comparable to the other. The close agreement of the two VIPs' results has increased the confidence of what will hopefully become one data point of many to create a database that *can* be used to extrapolate results to various sites and VIP types.

It would be insightful to compare the results of this data to that of pit latrines studied in Tanzania and Vietnam by the London School of Tropical Health and Hygiene (LSTH). Having seen the pits in Tanzania, a comparison of the pit chemical analysis at various depths, as was done in this study and is being done by LSTH, has the potential to reveal more about the variances in degradation. By examining the various water tables, user habits, pit structure and contents of pit latrines in Tanzania compared to VIPs in eThekwini, the degradation curve could be more standardised and the model made more robust.

This study has revealed several areas that could be further investigated to improve the understanding and confidence of the processes degrading VIP content. The following are possible future studies:

- Measure the characteristics of fresh faeces at time intervals such as 0h, 0.5h, 1h, 5h, 12h, etc. There are many rapid transformations that take place from the moment excreta leave the body and are exposed to ambient air to the instant it lands on the pit pile. Rapid sampling of fresh faeces would assist the understanding of the transition from fresh faeces to VIP content and possibly aid further in understanding degradation within the pit over a longer time.
- Determine the in-situ density of wet sludge at different depths in the VIP to better measure the mass of ash per volume of wet sludge. In this investigation it was assumed that the density of the sludge remained approximately 1 g/ml. More accurate sludge density and variation would improve the calculations based on this value, such as the relative ages of the material in each layer.
- Include potassium tests in all chemical analysis. Potassium is mainly found in urine and therefore would be a good indicator of the moisture being transferred out of the pit as urine and how much being transferred – or not transferred – is naturally occurring moisture in the air or soil. Determining the flow of urine through and around the pit would be useful to understand the transport and degradation of soluble components in the pit and to track the necessary subsurface flows.

- Test for soluble ash throughout the pit to determine if and how much soluble ash exited or entered the pit with water transport. Measurements of soluble ash would make the ash mass balance more comprehensive.
- A biodegradable COD analysis method to more accurately represent how biodegradable COD in the excreta degrades over the duration of time spent in the VIP. Running a more detailed analysis of the test with increased interim COD analyses would better indicate how long it takes to reach a plateau in the biodegradable COD, instead of assuming the biodegradable COD had been completely degraded after 2 weeks.
- Investigate soil characteristics surrounding a VIP to reveal valuable information regarding moisture transfer into and out of the pit under dry to saturated soil conditions. Testing the pore water pressure at radial distances could provide transportation explanations. This would also reveal which components are leaching into the surrounding soil and at what rate.
- A broader sample of external conditions, such as soil permeability, water table levels, slope, rainfall, temperature, number of users, pit dimensions and construction material. This study looked at two pits in close proximity with very similar characteristics. Expanding the range of pit conditions, users and designs would give a more holistic view of the degradation processes in a VIP and how they relate to the external conditions.
- Increased sampling at more frequent depth intervals. More sampling in the top 1 metre of the pit would be particularly useful as the model predicts that sludge characteristics change most rapidly in this section. However, the sampling would need to be done carefully to not mix layers. Even then, the model, both conceptual and mathematical, assumes that the material is built up uniformly in layers but in reality the additions form a conical pile where material subsides in different directions on each deposit. Additionally, a smooth curve depends on the model assumptions that material is added at constant rate and has a constant composition being valid. Under field conditions, even very accurate sampling would only give a general idea of what the degradation rates are because of inherent uncertainties in the sample age and original characteristics.
- Measure the volume of screened rubbish at designated depths. By measuring the volume of the rubbish content in each layer, one could study the transport and rate of input of rubbish depending on specific characteristics such as family size, user income, proximity to shops, and availability of household solid waste pick up.

- An economic assessment valuing the cost and benefits of providing solid waste removal system to the informal settlement areas. This could motivate the Municipality to supply a solid waste collection service where this is not already available. In additional to better health, safety, and improved environmental quality, having proper rubbish disposal for the households using VIPs would encourage people to not discard rubbish in the pit and therefore lead to less frequent VIP emptying.

8 References

Abrams, L. (2003). "The Water Page." African Water Toilet Designs and Operation.

APHA (1995). "Standard Methods." American Public Health Association, Washington, DC 19th Edition.

Bakare, B., et al. (July 2012). "Variation in VIP latrine sludge contents." Water SA. Volume 38. No. 4.

Bakare, B. F. (2008). Management of VIP Latrines in the eThekwini Municipality. WISA Conference. Sun City.

Brink, I., et al. (2006). "A Plant Wide Stoichiometric Steady State WWTP Model." University of Cape Town Department of Civil Engineering(Water Research Group).

Brouckaert, C. J., et al. (submitted 2012, Volume 38). "Modelling the filling rates of pit latrines." Water SA.

Buckley, C. and K. Foxon (2008). "Ventilated Improved Pit Latrines and the Efficacy of Pit Latrine Additives." Water Research Commission. TT 357/08.

Buckley, C., et al. (2008a). "Prevalence and Die-off of Ascaris Ova in Urine Diversion Waste." Water Research Commission. 1629/1/08.

Buckley, C., et al. (2008b). "Research into UD/VIDP Toilets: Physical and Health-Related Characteristics of UD/VIDP vault contents." Water Research Commission. 1629/1/08.

Buckley, C. A., et al. (2008c). "Scientific Support for the Design and Operation of Ventilated Improved Pit Latrines (VIPs) and the Efficacy of Pit Latrine Additives." Water Research Commission TT357/08**.**

Chaggu, E. J., et al. (2007). "Demonstration of anaerobic stabilization of black water in accumulation systems under tropical conditions." Bioresource Technology **98**(16): 3090-3097.

Crites, R. and G. Tchobanoglous (1998). Small and Decentralized Wastewater Management Systems. New York, McGraw-Hill.

Dhaar, G. and I. Robbani (2008). Foundations of Community Medicine. India, Elsevier.

DWAF (1994). White Paper: Water Supply and Sanitation Policy. Cape Town**:** 18, 34.

DWAF (2002). "Sanitation for a Healthy Nation: Sanitation Technology Options." Republic of South Africa February.

DWAF (2007). "Options for Dealing with Full Pits." Department of Water Affairs and Forestry (Draft Guideline- emptying of pit latrines).

Eckenfelder, W. W., et al., Eds. (1995). Activated Sludge: Process Design and Control. Pennsylvania, Technomic Publishing CO.

Eco-San (2011). What Happens When the Pit is Full. S. Report.

Ekama, G. A. (1984). "Theory, Design, and Operation of Nutrient Removal Activated Sludge Process." Water Research Commission Pretoria, South Africa.

Ekama, G. A. (2009). "Using bioprocess stoichiometry to build a plant-wide mass balance based steady-state WWTP model." Water Research 43(8): 2101-2120.

Ekama, G. A., et al. (2006). "Tracking the inorganic suspended solids through biological treatment units of wastewater treatment plants." Water Research 40(19): 3587-3595.

EPA (1993). "Standards for the Use or Disposal of Sewage Sludge; Final Rules." Federal Register 40 CFR Part 257.

EPA (2010). National Primary Drinking Water Regulations: List of Contaminants and their MLCs. Drinking Water Contaminants.

eThekwini (2010). Sewage Disposal Tariffs: Annexure A. e. Municipality. Durban.

EWS (2004). "Draft Water Services Development Plan." eThekwini Water and Sanitation Unit 2.

FAO (1997). "Renewable Biological Systems for Alternative Sustainable Energy Production." Agriculture Services Bulletin Chapter 4: Methane Production.

Foxon, K., et al. (2008). "Laboratory protocols for testing the efficacy of commercial pit latrine additives." WISA PRG(Sun City).

Foxon, K. M., et al. (2009). "Laboratory protocols for testing the efficacy of commercial pit latrine additives." Water SA 35(2).

Franceys, R., et al. (1992). "A guide to the development of on-site sanitation." WHO, Geneva.

Fritsch, A. (1990). "Dry Composting Toilets." Appalachia--Science in the Public Interest(A-SPI Technical Series TP-2).

GEO (2010). GEO Data Portal, United Nations Environment Programme.

Geurts, M. (2005). "Classification of Sanitation Systems." EcoSan WASTE: advisors on urban environment and development.

Gounden, T. (2008). Sustainable Sanitation in the eThekwini Municipality. e. Municipality, http://www.susana.org/lang-en/library?view=ccbktypeitem&type=2&id=790.

Haandel, A. C. V. and Marais (1981). "Nitrification and Denitrification Kinetic in the Activated Sludge Process." Civil Engineering Department: University of Cape Town Res. Rep. no W41(Res. Rep. no W41).

Hillel, D. (1998). Soil Moisture Characteristic Curve. Environmental Soil Physics. San Diego, Academic Press.

Itchon, G. S., et al. (2009). "The public health safety of using human excreta from urine diverting toilets for agriculture: the Philippine experience." Water, Sanitation and Hygiene: Sustainable Development and Multisectoral Approaches 34th WEDC International Conference(Addis Ababa, Ethiopia).

IWA (2002). "Anaerobic Digestion Model No. 1 (ADM1)." Task Group for Mathematical Modelling of Anaerobic Digestion Processes IWA Publishing.

Iwugo, K. O. (1981). "Sanitation technology options for developing countries (with special reference to Africa)." Public Health 95(4): 189-206.

Jönsson, H., et al. (2004). "Guidelines on the Use of Urine and Faeces in Crop Production." Stockholm Environment Institute EcoSanRes Publications Series(2).

Koné, D. and M. Strauss (2004). "Low-cost Options for Treating Faecal Sludges (FS) in Developing Countries -Challenges and Performance." EAWAG SANDEC.

Mara, D. D. (1984). "The Design of Ventilated Improved Pit Latrines."

Mara, D. D. (2004). Domestic wastewater treatment in developing countries. London, EARTHSCAN.

Metcalf and Eddy (2003). Wastewater Engineering Treatment and Reuse. New York, McGraw Hill.

Montessuit, C. (2010). "Laboratory Protocols for Testing the Efficacy of Commercial Pit Latrine Additives." Pollution Research Group and University of Joseph Fourier Internship Report.

Moodley, P. (2010). Savana Park VIP Interview. K. Wood. eThekwini.

Nwaneri, C. (2009). Physico-chemical characteristics and biodegradability of contents of ventilated improved pit latrines (VIPs) in eThekwini Municipality. Chemical Engineering. Durban, University of KwaZulu-Natal. Masters of Science.

O'Riordan, M. (2009). "Management of sludge accumulation in VIP latrines: Investigation into Methods of Pit Latrine Emptying." WRC Project 1745.

OXFAM (2009). "UD Toilets and Composting Toilets in Emergency Settings." OXFAM Technical Brief Eco San Latrine Construction.

Perrier, E. R., et al. (1960). "Pressure panel for Soil Moisture Removal measurements." California Agriculture(March): 13-14.

Perrow, M. R. and A. J. Davy, Eds. (2002). Handbook of Ecological Restoration. Chemical Treatment of Water and Sediments. Cambridge, Cambridge University Press.

Putnam, D. F. (1971). "NASA Contractor Report No. NASA CR-1802."

Russell, D. L. (2006). Practical Wastewater Treatment. New Jersey, John Wiley & Sons, Inc.

Scott, R. (1989). "Clean Waters: Wastewater Technical on Nitrogen." Atlantic States Rural Water & Wastewater Association.

Scott, R. and B. Reed (2006). "Emptying Pit Latrines." Loughborough University Water, Engineering and Development Centre- WELL.

Smith, P. G. and J. S. Scott (2002). Dictionary of Water and Waste Management. Boston, Butterworth-Heinemann.

Sobsey, M. (2006). "Excrement and Household Wastewater: Global Water, Sanitation and Hygiene." UNC.

Sophonsiri, C. and E. Morgenroth (2004). "Chemical composition associated with different particle size fractions in municipal, industrial, and agricultural wastewaters." Chemosphere(55).

Sterling, M. C. J., et al. (2001). "Effects of ammonia nitrogen on H_2 and CH_4 production during anaerobic digestion of dairy cattle manure." Bioresource Technology(77).

Still, D. and K. M. Foxon (in press 2012). "Tackling the Challenges of Full Pit Latrines." Water Research Commission.

Still, D. A. (2002). "After the Pit Latrine is Full...What Then? Effective Options for Pit Latrine Management." WISA.

Terrefe, A. and G. Edstrom (2007). "Ecological sanitation history, Sweden-Ethiopia." EcoSan.

Tilley, E., et al. (2008). "Compendium of Sanitation Systems and Technologies."

Trönnberg, L., et al. (October 2010). "Household-based prevalence of helminths and parasitic protosoa in rural KwaZulu-Natal, South Africa, assessed from faecal vault sampling." Transactions of the Royal Society of Tropical Medicine and Hygiene.

United Nations (2008). Millennium Development Goals Report 2008. New York.

WaterAid. (2009). "Latrine building in Ghana." Retrieved 08-12-2009. http://www.wateraidaustralia.org/australia/what_we_do/where_we_work/ghana/3395.asp.

Wentzel, M. C., et al. (1999). "Characterization of the Carbonaceous Material in Municipal Wastewaters." Water Research Group UCT.

WHO. (2003, 14 March 2011). "Emerging Issues in Water and Infectious Disease." Retrieved January 22, 2011.

WHO. (2011). "Fact Sheet 3.1: Excreta Disposal Options." Retrieved 14 March, 2011, from http://www.who.int/water_sanitation_health/emergencies/envsanfactsheets/en/index2.html.

WHO and UNICEF (2010). "Progress on Sanitation and Drinking-Water: 2010 Update." Joint Monitoring Programme for Water Supply and Sanitation.

WIN-SA (2006). "eThekwini's Water and Sanitation Programme." Lesson Series(2).

WRC (2007). "Design and Operating Requirements to Optimize the Life Span of VIP toilets." Sanitation Policy Brief.

Zakkour, P. D., et al. (2001). "Anaerobic treatment of domestic wastewater in temperate climates: treatment plant modelling with economic considerations." Water Research 35(17): 4137-4149.

Zhou, S. (2007). "Stoichiometry of biological nitrogen transformations in wetlands and other ecosystems." Biotechnology Journal 2(4): 497-507.

Appendices

Appendix I. Data

PIT 1

Layer	Depth [m]	Component	Units	a	b	c	Average	St Dev	Max	Min
1	0.00 ± 0.05	Moisture	g/g wet	0.72	0.80	0.76	0.76	0.041	0.760	0.760
2	0.50 ± 0.25	Moisture	g/g wet	0.84	0.78	0.77	0.80	0.036	0.797	0.797
3	1.00 ± 0.30	Moisture	g/g wet	0.45	0.38	0.40	0.41	0.033	0.409	0.409
4	2.00 ± 0.05	Moisture	g/g wet	0.50	0.47	0.56	0.51	0.044	0.512	0.512
1	0.00 ± 0.05	Total Solids	g/g wet	0.28	0.20	0.24	0.24	0.041	0.240	0.240
2	0.50 ± 0.25	Total Solids	g/g wet	0.16	0.22	0.23	0.20	0.036	0.203	0.203
3	1.00 ± 0.30	Total Solids	g/g wet	0.55	0.62	0.60	0.59	0.033	0.591	0.591
4	2.00 ± 0.05	Total Solids	g/g wet	0.50	0.53	0.44	0.49	0.044	0.488	0.488
1	0.00 ± 0.05	Volatile Solids	g/g wet	0.21	0.12	0.18	0.17	0.045	0.168	0.168
2	0.50 ± 0.25	Volatile Solids	g/g wet	0.10	0.16	0.17	0.14	0.038	0.143	0.143
3	1.00 ± 0.30	Volatile Solids	g/g wet	0.04	0.04	0.13	0.07	0.050	0.070	0.070
4	2.00 ± 0.05	Volatile Solids	g/g wet	0.11	0.17	0.12	0.13	0.032	0.131	0.131
1	0.00 ± 0.05	Ash	g/g wet	0.07	0.08	0.07	0.07	0.004	0.072	0.072
2	0.50 ± 0.25	Ash	g/g wet	0.06	0.05	0.06	0.24	0.005	0.060	0.060
3	1.00 ± 0.30	Ash	g/g wet	0.52	0.58	0.47	0.20	0.052	0.521	0.521
4	2.00 ± 0.05	Ash	g/g wet	0.39	0.36	0.32	0.59	0.034	0.357	0.357
1	0.00 ± 0.05	Alkalinity	mg-CaCO3/ g wet	81.3	89.2	84.9	0.49	3.955	85.54	84.46
2	0.50 ± 0.25	Alkalinity	mg-CaCO3/ g wet	87.0	86.8	82.0	0.17	2.831	85.74	84.66

3	1.00 ± 0.30	Alkalinity	mg-CaCO3/ g wet	45.5	45.9	48.9	0.14	1.858	47.19	46.41
4	2.00 ± 0.05	Alkalinity	mg-CaCO3/ g wet	31.3	33.6	30.0	31.63	1.823	31.73	31.08
1	0.00 ± 0.05	pH		7.88	7.86	7.85	7.86	0.015	7.88	7.85
2	0.50 ± 0.25	pH		7.73	7.62	7.66	7.67	0.056	7.91	7.62
3	1.00 ± 0.30	pH		7.31	7.31	7.43	7.35	0.069	7.43	7.31
4	2.00 ± 0.05	pH		7.83	7.56	7.56	7.65	0.156	7.83	7.56
1	0.00 ± 0.05	TKN	mg/g wet	4.68	6.44	3.92	5.01	1.293	5.02	5.00
2	0.50 ± 0.25	TKN	mg/g wet	9.52	9.12	5.6	8.08	2.157	8.09	8.07
3	1.00 ± 0.30	TKN	mg/g wet	16.92	6.12	4.08	9.04	6.900	9.05	9.03
4	2.00 ± 0.05	TKN	mg/g wet	44.72	6.04	5.48	5.76	0.396	5.77	5.75
1	0.00 ± 0.05	NH_4^+	mg/g wet	2.5	2.68	2.97	2.72	0.237	2.76	2.69
2	0.50 ± 0.25	NH_4^+	mg/g wet	0.64	0.71	0.76	0.70	0.060	0.74	0.66
3	1.00 ± 0.30	NH_4^+	mg/g wet	0.1	0.56	0.46	0.37	0.242	0.40	0.34
4	2.00 ± 0.05	NH_4^+	mg/g wet	-0.18	0.007	0.0007	-0.06	0.106	-0.03	-0.09
1	0.00 ± 0.05	PO_4 Total	mg/g wet	2.93	2.93	2.93	2.93	0.003	2.93	2.92
2	0.50 ± 0.25	PO_4 Total	mg/g wet	2.52	2.54	2.55	2.54	0.018	2.54	2.53
3	1.00 ± 0.30	PO_4 Total	mg/g wet	2.39	2.40	2.37	2.39	0.013	2.39	2.38
4	2.00 ± 0.05	PO_4 Total	mg/g wet	2.25	2.28	2.27	2.26	0.016	2.27	2.26
1	0.00 ± 0.05	OrthoPhos	mg/g wet	3.10	3.04	3.05	3.07	0.030	3.07	3.06
2	0.50 ± 0.25	OrthoPhos	mg/g wet	2.90	2.88	2.93	2.90	0.023	2.91	2.90
3	1.00 ± 0.30	OrthoPhos	mg/g wet	2.75	2.72	2.71	2.73	0.019	2.73	2.72
4	2.00 ± 0.05	OrthoPhos	mg/g wet	2.15	2.17	2.18	2.17	0.018	2.17	2.16
1	0.00 ± 0.05	COD_{total}	mg/g wet	105.33	100.66	92.53	99.51	6.475	99.92	99.10

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2	0.50 ± 0.25	COD_{total}	mg/g wet	96.77	93.26	105.24	98.42	6.159	95.28	94.46
3	1.00 ± 0.30	COD_{total}	mg/g wet	29.83	34.47	-190.73	32.15	3.284	34.04	33.35
4	2.00 ± 0.05	COD_{total}	mg/g wet	44.66	45.93	-88.52	45.30	0.894	48.30	47.67
1	0.00 ± 0.05	$COD_{particulate}$	mg/g wet	85.47	86.10	87.66	86.41	1.129	86.18	85.39
2	0.50 ± 0.25	$COD_{particulate}$	mg/g wet	80.24	91.88	84.33	85.48	5.906	88.04	87.23
3	1.00 ± 0.30	$COD_{particulate}$	mg/g wet	29.62	30.86	26.83	29.10	2.061	27.48	26.81
4	2.00 ± 0.05	$COD_{particulate}$	mg/g wet	46.98	40.66	38.13	41.93	4.558	41.19	40.56
1	0.00 ± 0.05	$COD_{soluble}$	mg/g wet	16.23	15.29	12.17	14.56	2.124	13.32	12.67
2	0.50 ± 0.25	$COD_{soluble}$	mg/g wet	15.42	3.78	11.96	10.38	5.979	9.92	9.27
3	1.00 ± 0.30	$COD_{soluble}$	mg/g wet	2.06	3.30	0.83	2.06	1.238	0.52	-0.10
4	2.00 ± 0.05	$COD_{soluble}$	mg/g wet	0.21	1.16	0.84	0.74	0.483	0.53	-0.11
1	0.00 ± 0.05	$COD_{TotBiodeg}$	mg/g wet	81.61	77.98	78.49	79.36	1.967	79.76	78.97
2	0.50 ± 0.25	$COD_{TotBiodeg}$	mg/g wet	34.14	36.66	35.09	35.29	1.272	36.22	35.52
3	1.00 ± 0.30	$COD_{TotBiodeg}$	mg/g wet	27.66	33.23	15.27	25.39	9.191	25.72	25.05
4	2.00 ± 0.05	$COD_{TotBiodeg}$	mg/g wet	3.16	5.69	2.84	3.90	1.559	2.53	1.89
1	0.00 ± 0.05	$COD_{PartBio}$	mg/g wet	43.67	44.93	42.42	43.67	1.252	44.66	43.94
2	0.50 ± 0.25	$COD_{PartBio}$	mg/g wet	22.81	30.37	37.29	30.16	7.240	30.50	29.81
3	1.00 ± 0.30	$COD_{PartBio}$	mg/g wet	22.45	21.21	23.99	22.55	1.396	14.41	13.76
4	2.00 ± 0.05	$COD_{PartBio}$	mg/g wet	1.58	0.00	0.95	0.84	0.795	1.11	0.47
1	0.00 ± 0.05	COD_{SolBio}	mg/g wet	17.16	7.18	8.11	10.82	5.52	12.54	11.89
2	0.50 ± 0.25	COD_{SolBio}	mg/g wet	7.76	10.91	5.24	7.97	2.838	10.39	9.74
3	1.00 ± 0.30	COD_{SolBio}	mg/g wet	3.51	3.20	4.75	3.82	0.819	3.74	3.12
4	2.00 ± 0.05	COD_{SolBio}	mg/g wet	0.00	4.42	2.53	2.32	2.220	2.53	1.89

PIT 2

Layer	Depth [m]	Component	Units	a	b	c	Average	St Dev	Max	Min
1	0.00 ± 0.05	Moisture	g/g wet	0.79	0.79	0.79	0.79	0.002	0.789	0.789
2	0.50 ± 0.25	Moisture	g/g wet	0.68	0.73	0.59	0.67	0.070	0.666	0.666
3	1.00 ± 0.30	Moisture	g/g wet	0.52	0.52	0.50	0.51	0.012	0.512	0.512
4	2.00 ± 0.05	Moisture	g/g wet	0.64	0.64	0.62	0.63	0.012	0.634	0.634
1	0.00 ± 0.05	Total Solids	g/g wet	0.21	0.21	0.21	0.21	0.002	0.211	0.211
2	0.50 ± 0.25	Total Solids	g/g wet	0.32	0.27	0.41	0.33	0.070	0.334	0.334
3	1.00 ± 0.30	Total Solids	g/g wet	0.48	0.48	0.50	0.49	0.012	0.488	0.488
4	2.00 ± 0.05	Total Solids	g/g wet	0.36	0.36	0.38	0.37	0.012	0.366	0.366
1	0.00 ± 0.05	Volatile Solids	g/g wet	0.16	0.15	0.15	0.15	0.006	0.152	0.152
2	0.50 ± 0.25	Volatile Solids	g/g wet	0.13	0.13	0.11	0.12	0.011	0.122	0.122
3	1.00 ± 0.30	Volatile Solids	g/g wet	0.08	0.07	0.08	0.08	0.005	0.078	0.078
4	2.00 ± 0.05	Volatile Solids	g/g wet	0.12	0.12	0.11	0.12	0.005	0.120	0.120
1	0.00 ± 0.05	Ash	g/g wet	0.24	0.30	0.30	0.28	0.032	0.059	0.059
2	0.50 ± 0.25	Ash	g/g wet	0.60	0.53	0.73	0.62	0.105	0.213	0.213
3	1.00 ± 0.30	Ash	g/g wet	0.83	0.85	0.84	0.84	0.010	0.410	0.410
4	2.00 ± 0.05	Ash	g/g wet	0.66	0.66	0.70	0.67	0.025	0.247	0.247
1	0.00 ± 0.05	Alkalinity	mg-CaCO3/ g	129.6	124.7	122.0	125.43	3.853	126.10	124.70
2	0.50 ± 0.25	Alkalinity	mg-CaCO3/ g	110.2	105.1	96.5	103.93	6.924	104.42	103.19
3	1.00 ± 0.30	Alkalinity	mg-CaCO3/ g	37.0	38.6	42.7	39.43	2.940	39.96	39.24

4	2.00 ± 0.05	Alkalinity	mg-CaCO3/ g	23.8	23.5	24.8	24.03	0.681	24.30	23.71
1	0.00 ± 0.05	pH		8.52	8.62	8.39	8.51	0.115	8.62	8.39
2	0.50 ± 0.25	pH		9.01	8.88	8.81	8.90	0.101	9.01	8.81
3	1.00 ± 0.30	pH		8.77	8.86	8.87	8.83	0.055	8.87	8.77
4	2.00 ± 0.05	pH		7.9	7.63	7.74	7.76	0.136	7.90	7.63
1	0.00 ± 0.05	TKN	mg/g wet	8.84	5.56	6.68	7.03	1.667	7.48	7.02
2	0.50 ± 0.25	TKN	mg/g wet	7.32	7.40	10.20	8.31	1.640	8.32	8.30
3	1.00 ± 0.30	TKN	mg/g wet	0.04	6.80	7.32	7.06	0.368	7.07	7.05
4	2.00 ± 0.05	TKN	mg/g wet	5.36	5.48	6.76	5.87	0.776	5.88	5.86
1	0.00 ± 0.05	NH_4^+	mg/g wet	2.39	1.90	1.76	2.02	0.331	2.08	2.00
2	0.50 ± 0.25	NH_4^+	mg/g wet	2.71	2.73	2.67	2.70	0.031	2.76	2.72
3	1.00 ± 0.30	NH_4^+	mg/g wet	1.09	1.76	1.65	1.50	0.359	1.54	1.47
4	2.00 ± 0.05	NH_4^+	mg/g wet	1.65	1.02	1.09	1.25	0.345	1.29	1.21
1	0.00 ± 0.05	PO_4 Total	mg/g wet	2.92	2.93	2.94	2.93	0.011	2.93	2.92
2	0.50 ± 0.25	PO_4 Total	mg/g wet	2.72	2.73	2.74	2.73	0.013	2.74	2.73
3	1.00 ± 0.30	PO_4 Total	mg/g wet	1.38	1.41	1.42	1.41	0.018	1.41	1.40
4	2.00 ± 0.05	PO_4 Total	mg/g wet	1.85	1.86	1.86	1.86	0.006	1.86	1.85
1	0.00 ± 0.05	OrthoPhos	mg/g wet	3.23	3.26	3.21	3.23	0.026	3.24	3.23
2	0.50 ± 0.25	OrthoPhos	mg/g wet	2.78	2.75	2.89	2.81	0.073	2.82	2.81
3	1.00 ± 0.30	OrthoPhos	mg/g wet	0.65	0.67	0.68	0.67	0.012	0.67	0.66
4	2.00 ± 0.05	OrthoPhos	mg/g wet	0.65	0.66	0.70	0.67	0.026	0.68	0.66
1	0.00 ± 0.05	COD_{total}	mg/g wet	79.27	49.78	65.85	64.97	14.765	65.39	64.64

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2	0.50 ± 0.25	COD_{total}	mg/g wet	48.22	69.36	51.69	56.42	11.338	59.03	59.03
3	1.00 ± 0.30	COD_{total}	mg/g wet	29.33	31.18	26.53	29.01	2.340	30.55	29.86
4	2.00 ± 0.05	COD_{total}	mg/g wet	47.10	39.05	37.43	41.20	5.180	39.05	38.35
1	0.00 ± 0.05	$COD_{particulate}$	mg/g wet	52.06	59.02	61.23	57.44	4.785	55.91	55.17
2	0.50 ± 0.25	$COD_{particulate}$	mg/g wet	39.15	46.07	45.12	43.45	3.751	42.73	42.01
3	1.00 ± 0.30	$COD_{particulate}$	mg/g wet	29.39	30.32	-115.08	29.85	0.656	32.21	31.52
4	2.00 ± 0.05	$COD_{particulate}$	mg/g wet	42.07	38.67	40.22	40.32	1.704	42.81	42.10
1	0.00 ± 0.05	$COD_{soluble}$	mg/g wet	14.18	-271.99	23.64	18.91	6.686	19.31	18.64
2	0.50 ± 0.25	$COD_{soluble}$	mg/g wet	10.43	16.76	0.63	9.27	8.125	5.86	5.21
3	1.00 ± 0.30	$COD_{soluble}$	mg/g wet	3.40	1.24	6.50	3.71	2.643	3.90	3.27
4	2.00 ± 0.05	$COD_{soluble}$	mg/g wet	4.64	6.19	-0.31	3.51	3.394	3.86	3.23

Appendix II. Sample Calculations

1) Convert concentration to an ash basis [mg X/g ash]

C_{iw} = concentration of species *i* in VIP contents [mg *i* / g wet sludge]

C_{ts} = concentration of total solids [g dry sludge/ g wet sludge]

C_{id} = concentration of species *i* in VIP contents [mg *i* / g dry sludge]

C_{ash} = concentration of ash [g ash/g wet sludge]

$$\frac{Ciw}{Cts} = \frac{mg\ i}{g\ wet\ sludge} * \frac{g\ wet\ sludge}{g\ dry\ sludge} = \frac{mg\ i}{g\ dry\ sludge} = C_{id}$$

$$\frac{Ciw}{Cash} = \frac{mg\ i}{g\ wet\ sludge} * \frac{g\ wet\ sludge}{g\ ash} = \frac{mg\ i}{g\ ash} = C_{ia}$$

2) Mass Ash per Volume wet sludge

Assuming density of wet sludge is 1 g/ml

$$C_{ash} = \frac{g\ ash}{g\ wet\ sludge} * \frac{1\ g\ wet\ sludge}{1\ ml\ wet\ sludge} = \frac{g\ ash}{ml\ wet\ sludge} * \frac{1\ kg}{1000\ g} * \frac{1000\ ml}{1\ l} = \frac{kg\ ash}{l\ wet\ sludge} * \frac{1000\ l\ wet\ sludge}{1\ m^3\ wet\ sludge} = \frac{1000\ kg\ ash}{m^3\ wet\ sludge}$$

3) Mass ash per pit

Assuming cross-sectional area of pit is 1 m^2

X = layer in pit

Continuing from mass ash per volume wet sludge…

$$\frac{1000\ kg\ ash}{1\ m^3\ wet\ sludge} * (depth\ of\ layer\ x - depth\ of\ layer\ (x-1)\ in\ m) = \frac{1000\ kg\ ash}{m^2\ wet\ sludge} * 1\ m^2 = \frac{1000\ kg\ ash}{layer\ x}$$

$$\frac{kg\ ash}{pit} = \sum_{layer\ n}^{layer\ 0} \frac{1000\ kg\ ash}{layer\ x}$$

4) Age of material per layer

Assume ash content of fresh faeces is 0.11 g ash/ g wet sludge sample

Assume per capita fresh faeces production is 51 kg/ year

ff = fresh faeces

P = people using pit per household.

Continuing from Mass ash per pit…

$$\frac{kg\ ash}{pit} * \frac{1\ kg\ ff}{110\ kg\ ash} = \frac{kg\ ff}{110\ pit} * \frac{person-year}{51\ kg\ ff} = \frac{person-year}{5610\ pit} * \frac{pit}{\mathrm{P}\ people} = \frac{years}{5610\ \mathrm{P}} =$$

estimated years of use (age of pit material)

Continuing from penultimate step of mass ash per pit to get the ratio of ash mass per layer of total ash mass per pit…

$$\frac{1000\ kg\ ash}{layer\ \ x} * \frac{1\ pit}{kg\ ash} = \frac{1000\ pit}{layer\ x}$$

$$\frac{1000\ pit}{layer\ x} * \frac{years}{5610\ \mathrm{P}} = \frac{1000\ pit\ years}{layer\ x\ 5610\ \mathrm{P}}$$ = age in years of the material in layer x relative to estimated years of use

5) Fresh Faeces Equivalents

Provides the kg of fresh faeces necessary to leave the ash concentration found

Assume ash content of fresh faeces is 0.11 g ash/ g wet sludge sample

$$\frac{kg\ ash}{layer\ \ x} * \frac{kg\ wet}{0.11\ kg\ ash} = \frac{kg\ wet}{0.11\ layer\ x}$$

6) Rate of Rubbish input

Using the ratio of ash mass per layer of total ash mass for each pit and 25% as the observed rubbish content in VIPs taken from the literature, the volume of the rubbish in each layer is calculated, assuming ash and rubbish are conserved in the pit.

$$\frac{g\ ash}{layer\ \ x} * \frac{pit}{g\ ash} * estimated\ rubbish\ volume\ \%\ (.25) * pit\ volume\ m3\ (2.8) = \frac{m3\ rubbish}{layer\ x}$$

Pit 1	% ash of total	Layer Volume [m^3]	Volume Rubbish [m^3]	Rubbish [%]	Age [years]	Fill Rate [m^3/y]
Layer 1	0.08	0.7	0.05376	0.0768	1.18	0.045559
Layer 2	0.26	0.7	0.17472	0.2496	5.18	0.03373
Layer 3	0.66	1.4	0.44352	0.3168	15.65	0.02834
			0.672	0.24		0.033992

Pit 2	% ash of total	Layer Volume [m3]	Volume Rubbish [m3]	Rubbish [%]	Age [years]	Fill Rate [m^3/y]
Layer 1	0.15	0.7	0.1008	0.144	2.42	0.041653
Layer 2	0.28	0.7	0.18816	0.2688	5.55	0.033903
Layer 3	0.58	1.4	0.38976	0.2784	11.71	0.033284
			0.67872	0.2424		0.035531

Dividing by the number of years each layer has been used as found using the depth age relationship previously gives the rate of rubbish input in m^3/ year.

Integrating these rates over the pit layer depths gives fill rate for Pit 1 of 0.034 m^3/y and for Pit 2 0.036 m^3/y. The calculated input rate of excreta is 0.36 m^3/year based on the assumptions shown below. The rubbish input rate is approximately 10% of the excreta input rate.

7) Height of rubbish per layer

Finds the height of the rubbish per layer if segregated from the excreta.

Find the faecal input rate:

$$\frac{51\ kg\ fresh\ faeces}{person\ year} * 7\ people = \frac{357\ kg}{year} * \frac{1\ m3}{1000\ kg} = 0.357 \frac{m3}{y} / \frac{1}{1.4\ m2} = 0.255\ m/y$$

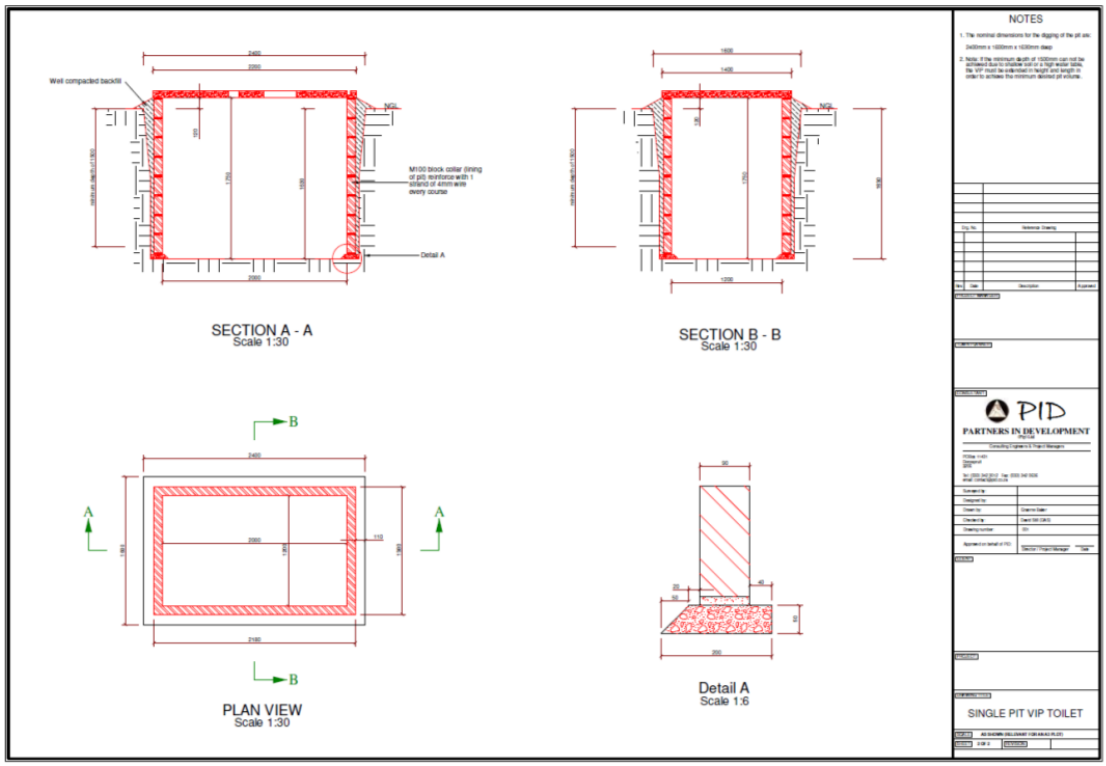
Find the rubbish height using the 10% assumption:

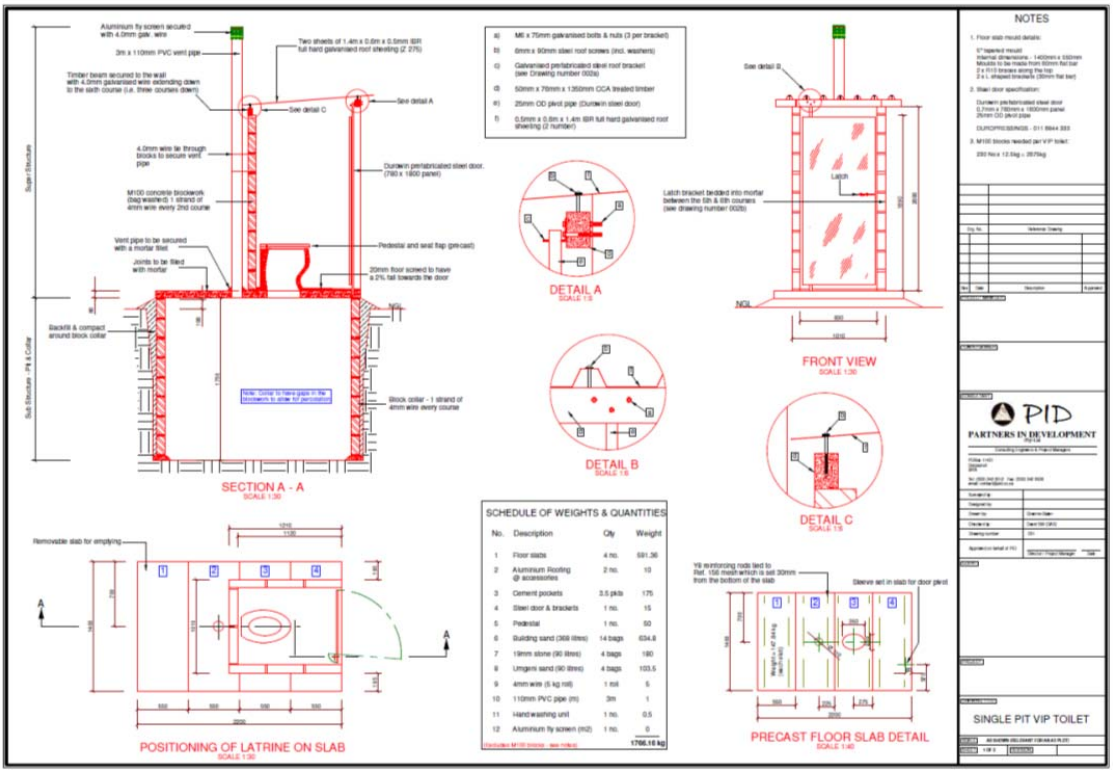
Faecal input rate as 0.255 $\frac{m}{y}$ * age of the layer in years found previously * 0.10 = rubbish height per layer in metres

8) Average density of rubbish

Density of Rubbish		
glass	2600	[kg/m^3]
plastic	940	[kg/m^3]
cloth	1540	[kg/m^3]
cardboard	90	[kg/m^3]
	1292.5	[kg/m^3]

Appendix III. Example of single pit VIP design dimensions





Appendix IV. Submitted version of *Modelling the filling rate of pit latrines, 2012*