ENTRENCHMENT OF PIT LATRINE AND WASTEWATER SLUDGES
AN INVESTIGATION OF COSTS, BENEFITS, RISKS AND REWARDS

Report to the
Water Research Commission
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The publication of this report emanates from a project titled: "An Investigation into the long term risks associated with deep row entrenchment of pit latrine and wastewater treatment works sludge for forestry and land rehabilitation purposes" (WRC Project No. K5/2097). This project has been an extension of the WRC Project K5/1839, which was titled "Investigating the potential of deep row entrenchment of pit latrine and wastewater treatment works sludge for forestry and land rehabilitation purposes".

EXECUTIVE SUMMARY

Decent sanitation is fundamental to public health. The realisation of this truth and the implementation of measures to achieve it has arguably saved more lives than any medical advance in history[1]. While there are a wide range of sanitation technologies in use, they can be split into those which deal with the waste off site using some form of wastewater treatment, and those which retain the waste on site. In South Africa the two overwhelmingly dominant forms of sanitation are fully waterborne sanitation in towns and cities (i.e. from a flush toilet via a sewer system to a wastewater treatment plant) and the septic tank or pit latrine in non-sewered areas. An end product of both of these systems is an accumulation of what is termed "sludge" (or "biosolids").

The sludge produced by a wastewater treatment plant depends on the technology employed and the stage of the process from which it emanates. However, the greater portion of wastewater treatment plant sludge in South Africa is what is termed secondary activated sludge, being a concentration of the biota which feed on the nutrients in the sewage. The sludge removed from a pit latrine or a septic tank is concentrated faeces in various states of decomposition, depending on how long it has been in the pit or tank. Although the numbers vary considerably according to a range of factors and circumstances, with pit latrines and septic tanks, faecal sludge typically accumulates at a rate of 30 to 50 litres per person per year. At a wastewater treatment plant, typically 1 m^3 of sludge is produced per day per Mℓ of sewage processed, although this volume can be reduced by up to 80% if it is further processed in anaerobic digestors.

All this sludge accumulates and must ultimately be disposed of. Options for the disposal of secondary sludge from sewage plants include landfill, incineration, composting, surface application and irrigation. Septage (sludge removed from septic tanks) is generally disposed of at wastewater treatment plants. Sludge removed from pit latrines, however, is more difficult to deal with. It often contains a certain amount of non-faecal solid matter such as rags, plastic bags and disposable nappies. It may also contain a high load of pathogenic organisms such as helminth ova (worm eggs). Disposal of faecal sludge is therefore more difficult than is the disposal of secondary wastewater sludge. With good management and control pit sludge can be composted. Irrigation is not feasible. Conventional landfill sites are not suited for the disposal of fresh faecal waste. eThekwini Metropolitan Municipality (Durban) has been working on a machine which is able to pelletise pit sludge, making a low strength organic fertilizer. However this process, known as LaDePa (Latrine Bio-solids Dehydration and Pasteurisation), is neither simple nor cheap (the processing of pit sludge by this method is estimated to cost approximately R2 000 per m^3 of wet sludge, excluding the cost of pit emptying and sludge transport). Another option which is currently gaining interest is the use of Black Soldier Fly Larvae (BSFL), a naturally occurring non-invasive insect which feeds on rotting organic matter. A BSFL process converts sludge mixed with food waste into organic waste products which proponents claim is pathogen free and can be turned into high value chicken and fish feed and soil conditioner.

There are advantages and disadvantages to all of the above disposal options, and each has its place. However, by far the simplest and most economical method for the disposal of sludge is simply to bury it as close as possible to the removal site. Burial deals with the problems of odour and insects, and protects people from accidental contact with the pathogens in the sludge. Furthermore the nutrients in the sludge can potentially act as fertilizer for crops (e.g. sugarcane, fruit trees or timber).

[1] In a survey of 11 000 readers conducted by the British Medical Journal in January 2007, improvements in sanitation were voted as the most significant cause of public health improvements in modern times, narrowly edging out antibiotics and anaesthesia.

The possible risk is that the nitrates and phosphates in the sludge will leach into the groundwater and thus impact negatively on the environment in the vicinity of the burial site. There might also be a concern that the pathogens in the sludge will remain active and will pose a long term risk if the sludge is later dug up. The work described in this report has investigated the benefits and risks of sludge entrenchment.

Five experiments are described in this report. In the first two pit latrines were emptied at Inadi near Pietermaritzburg and the sludge was used to fertilize and condition the soil around new fruit trees which were planted at the homesteads. Citrus and peach trees were the trees selected by the families, and particularly in the case of the citrus those trees which were planted with sludge grew noticeably larger and had more abundant fruit. The size of this experiment was too small to be of much scientific significance, but perhaps the most important finding was that the planting of trees over faecal sludge and the consumption of the fruit that grew on those trees was not considered taboo.

In the second experiment 24 trees, 12 with sludge and 12 without, were planted in one metre high and 0.75 m diameter concrete towers, and closely monitored for six months. At the end of the six months the towers were broken up, and the total tree mass for each tower was measured. The pattern and density of the roots were also studied. The 24 trees were split evenly between eucalyptus and wattle. In the case of the experimental trees, a core of pit latrine sludge was placed at the centre of the tower directly below the sludge. Throughout the experimental period the control trees, those without sludge, were given liquid fertilizer, while the experimental trees were given just water (the same amount as that given to the controls). The growth response of the experimental eucalyptus trees was strikingly better than the controls, while that for the wattle trees was less so. In the case of the experimental trees the tree roots were denser around the outer edges of the soil where they were turned by the concrete wall, but the roots also grew into the sludge core below the trees.

In the third experiment over a thousand cubic metres of pit latrine sludge was buried on the site of an old oxidation pond in Umlazi, south of Durban. Eucalyptus and wattle trees were planted over the sludge and five monitoring boreholes were drilled between the site and the nearby Umlazi river. No significant changes were detected in the groundwater over a two year monitoring period. Samples of the sludge were taken from time to time and assessed for physical properties and pathogen content. After three years the sludge was hard to distinguish from the surrounding soil, the organic matter had virtually all decomposed and the pathogens (using *Ascaris* as a marker) had all died.

In the fourth experiment some 360 cubic metres of wastewater treatment works activated sludge was buried in a eucalyptus plantation near Howick in the Natal midlands. The two hectare experimental area was divided into 30 plots each 30 by 30 metres in extent, and in 18 of these plots sludge was buried in a 20 by 20 metre section in the centre of the plot. Five treatments were compared: T1 had one 10 m^3 load of sludge, T2 had two loads, T3 had three loads, T4 had no sludge but it did have trenches, and T5 had no sludge and also no trenches. With the growth of 900 trees (30 at the centre of each plot) having been observed from planting in January 2010 until May 2014, a period of 52 months, the plots with sludge show a 50% increase in timber volume compared with those without. This site has also been closely monitored for groundwater impact, using a number of piezometers for near surface flow and two 60 metre deep boreholes at the bottom of the site for groundwater monitoring. Only a small difference (2 mg/ℓ) in nitrate levels was detected in the downstream borehole compared with the upstream borehole over the first year after planting, and after four years the nitrate content in the water sampled from the site rain gauge was significantly higher than that sampled from the boreholes or the piezometers. Samples of soil taken after 3 years from around the buried sludge and from the sludge itself show that nitrogen is not retained in the sludge or in the surrounding soil, whereas potassium, phosphorus and other elements such as calcium and zinc are retained.

The final experiment, which is ongoing, is looking more closely at the leachate emanating from buried WWTW sludge in a set of 15 one metre square plots, 12 of which have a layer of either 250 mm or 500 mm of sludge. Six of these plots have been constructed with pan lysimeters buried some 500 mm below the sludge, which means that all the leachate which seeps downwards from the sludge (and in this case instrumentation detects no lateral seepage) is captured and can be analysed. After ten months of monitoring through the rain season of 2013/2014 less than 0.2% of the nitrogen and less than 0.003% of the phosphorus has been detected in the leachate. As the fourth experiment described above showed that within three years the nitrogen in the sludge is no higher than background soil levels, this evidence supports the hypothesis that most of the nitrogen that is buried in sludge returns to the atmosphere through the natural processes of nitrification and denitrification.

This study provides or at least suggests answers to a number of questions regarding sludge entrenchment, as follows:

Has this method of sludge disposal been tried before?

Entrenchment as a disposal method for wastewater treatment works sludge was pioneered in Maryland, United States in the mid-70s and has been the subject of extensive research since that time. The Maryland research, later extended to Philadelphia, indicates that entrenchment is a safe method for sludge disposal. Repeated trials over more than 20 years have not detected a significant impact on the groundwater, despite very heavy application rates (up to 660 dry tons per hectare). Trials with fast growing poplar trees indicate that tree growth is significantly enhanced when these trees are planted in close proximity to the entrenched sludge.

What is the fate of pathogens which are buried in the ground?

The ovum of *Ascaris lumbricoides* (roundworm) is considered to be the hardiest of pathogens in faecal sludge and is therefore used as a marker organism for determining the degree to which sludge can be considered safe to handle. *Ascaris* is rife in Durban and sludge removed from pit latrines typically has average egg counts of several hundred ova per gram of sludge. The presence of *Ascaris* has been monitored in buried sludge over a period of 48 months and these results show a complete die off over a period of three to four years. It can therefore be reasonably concluded that, assuming there was any reason to do it, buried sludge can be safely dug up after 4 years. Tests for the presence of *Ascaris* on surface soil samples after 48 months indicated no significant difference between the soil in the entrenchment area and background soil samples from a similar area where no sludge had been handled.

How does sludge change after it is buried in the ground?

Over time sludge buried in the soil dewaters and decomposes. After several years it is difficult to distinguish from the surrounding soil. Over the course of four years the pit sludge buried at Umlazi changed as follows:

- The median COD decreased from 0.25 g COD/g dry sample to 0.05 g COD/g dry sample
- The median volatile solids decreased from 60% to 3%
- The moisture content reduced from 75% to 13%

These data indicate that the organic matter has largely decomposed over the four year period.

What is the fate of the nutrients in the sludge after it is buried in the ground?

High concentrations of nitrogen and phosphate have been observed in the leachate in the immediate proximity to the sludge, and occasional spikes of high nitrate and phosphate have been observed in the subsurface flow at drainage lines below the Sappi site, which has a fairly shallow soil over a shale layer with low permeability. However no significant increases in nitrate or phosphate have been detected over the monitoring period in any of the boreholes located between the sludge entrenchment sites and the nearest downslope streams. After three years the phosphorus and potassium levels in the soil immediately around the sludge are raised, but within less than a metre are no different to background levels. After three years there is no significant difference between the nitrogen levels in the sludge, in the soil around the sludge and in the background soil. A set of very well controlled leachate monitoring trials on different soils on sloping ground (which are ongoing) show that after four months less than 0.2% of the nitrogen has leached out of the sludge, and less than 0.004% of the phosphorus has leached. While some of the N and P has been taken up in the trees this will only account for a small percentage of the nutrient loading. It is probable that much of the P has bonded with clay particles in the soil in the immediate vicinity of the sludge and has not moved far, while it is probable that much of the excess N introduced to the soil has been recycled back to the atmosphere by nitrifying and denitrifying bacteria. Further work is required to better understand these natural processes.

How should one go about burying sludge in the ground and what will this cost?

The Maryland, United States entrenchment work which inspired this research is based on maximizing disposal as opposed to maximising nutrient uptake/beneficiation. While the Umlazi and Sappi trials described here have not detected any negative environmental effects, it would make sense to apply smaller amounts of sludge more often if one is to maximize the nutrient uptake in the crops which are intended to benefit from the process. However, that said, it would be inefficient and expensive to bury very small amounts of sludge.

Sludge entrenchment lends itself to labour intensive methods, which maximize employment. The sludge should be transported in sealed drums to prevent spillage and wastage. These drums should be sized appropriately for labour intensive loading, offloading and haulage methods (i.e. not more than say 70 litres of sludge per drum). Trenches should be dug no more than a spade width (300 mm) and 400 mm in depth. These trenches should be filled with sludge to a depth of 300 mm and then backfilled. The surplus soil should be mounded over the trench as the sludge will reduce approximately 50% in volume as it dewaters and decomposes. If trenches of these dimensions are dug between all rows in a plantation (assuming a spacing between rows of 3 metres) the total amount of sludge buried will amount to approximately 140 dry tons/hectare.

The cost of sludge entrenchment can be expected to cost approximately R60 000 per hectare, assuming an entrenchment rate of 300 m^3 of wet sludge per hectare and a haulage distance of 30 km, i.e. R200/m^3. At approximately R3.20/m^3.km transport quickly becomes the dominant factor in the cost calculation. Further costs will be incurred establishing leachate and groundwater monitoring well points, which might amount to several hundred thousand Rands. A monitoring establishment cost of R10 000 per hectare is a reasonable budget figure (assuming that one monitoring well will cover at least 10 hectares).

Other methods of sludge disposal, for example using landfills, incineration, pelletizing and composting can be considerably more expensive.

Can one make use of the nutrients in the buried sludge, and what might such use be worth?

In the trials conducted as part of this research the results indicate that timber tonnage will increase by up to 50% for plots with entrenchment relative to those using conventional methods of fertilisation. Over a 10 year growing cycle this would translate into increased revenue of R25 000 at current prices. This is less than the cost of entrenching the sludge, but it does nevertheless offset the cost of the sludge disposal.

What are the alternatives to this method of sludge disposal, and what do such methods cost?

Municipalities in South Africa are used to dealing with wastewater treatment works sludge disposal. Very few, however, have to date tackled the disposal of pit latrine sludge at any scale, with eThekwini being the only notable exception.

Wastewater Treatment works sludges are generally disposed of in landfills, or they are composted. In some cases they are irrigated or surface spread after stabilisation using anaerobic digestion or lime addition. Landfill and composting are fairly expensive processes, with costs in the order of R500 m^3 being reported.

If one wishes to use this method for sludge disposal, how should one go about acquiring authorisation from the relevant authorities?

Unless one is dealing with small volumes of sludge (literally the contents of just a few pit latrines) which is being disposed of on or near the site where it originated, then an Environmental Impact Assessment (EIA) will have to be undertaken in order for entrenchment to be used at any scale worth the effort. The EIA must be done by an independent professional and will involve stakeholder consultation, specialist studies and the review of alternatives, risks and benefits. This process is lengthy and expensive (for example, a one to two year process costing anywhere from R100 000 to R500 000 is not unlikely). It would therefore make sense to acquire authorisation for a large scale, long term DRE programme where one EIA can cover all that will be required for, say, a 10 year planning horizon.

Summary

No other method of sludge disposal is more economical than simply burying it in the ground, especially if the burial site is close by the site where the sludge is collected. In the ground, sludge decomposes by natural biological processes and after a few years is barely distinguishable from the surrounding soil. After three years even the hardiest pathogens such as *Ascaris* die off. Despite high loading rates no significant impact on groundwater has been observed in the trials to date over four years of monitoring, and there is evidence that the phosphorus and potassium in the sludge binds to soil particles near the point of burial while the nitrogen returns to the atmosphere.

When sludge is buried in close proximity to eucalyptus trees, which form a major part of the South African forestry plantations, growth is enhanced by up to 50% in terms of total timber volume, although after only four years it is too soon to say if the magnitude of this difference will be sustained over a nine or ten year growth cycle. This additional timber volume will offset the cost of the entrenchment process by as much as a third or even a half. The increased potassium and phosphorus levels in the soil will be lasting and will benefit future tree growth cycles.

Entrenchment provides a practical and beneficial technique to deal with the problem of disposal of potentially dangerous faecal sludge from pit latrines and wastewater treatment works. Unfortunately it is still too little known or understood in South Africa and it is improbable that permission will easily be obtained to adopt this method at scale.

It would be advisable to continue with the monitoring of the experimental plot at Sappi's Shafton plantation to see whether the enhanced growth in the plots with sludge is fully sustained to the end of the ten year growth cycle, i.e. to December 2019. This work would not require a significant research budget, as all that would have to be done would be to measure the trees once per year and to sample the boreholes perhaps twice per year.

Meanwhile it is quite possible that other methods of sludge burial might yield better results compared with these trials. For example smaller amounts of sludge could be buried but with a greater frequency – say once every three years in the same location. It is recommended that trials are conducted comparing different entrenchment methods to see which gives the best return on investment.

These trials have been carried out with agroforestry in mind. It is not recommended that sludge is used as a fertilizer or soil conditioner in close proximity to food crops such as vegetables. However South Africa and in particular KwaZulu-Natal has a large sugar cane industry, and it is recommended that trials be conducted with sugar cane instead of eucalyptus trees as the associated crop. Entrenchment in a cane field would be significantly easier than entrenchment in a forestry plantation, due to the absence of roots and stumps.

Finally, more work must be done to fully understand the fate of the nitrogen and phosphorus in the buried sludge. On the strength of the evidence in this study, only a very small fraction of these elements leach out of buried sludge. This implies that a significant fraction of the remainder either stays where it is (adsorbed to the soil, in the case of phosphorus) or returns to the atmosphere (in the case of nitrogen). More rigorous and long term work is required to prove these hypotheses.

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1. BACKGROUND AND INTRODUCTION

Decent sanitation is fundamental to public health. The realisation of this truth and the implementation of measures to achieve it has arguably saved more lives than any medical advance in history[1]. While there are a wide range of sanitation technologies in use, they can be split into those which deal with the waste off site using some form of wastewater treatment, and those which retain the waste on site. In South Africa the two overwhelmingly dominant forms of sanitation are fully waterborne sanitation in towns and cities (i.e. from a flush toilet via a sewer system to a wastewater treatment plant) and the septic tank or pit latrine in non-sewered areas. An end product of both of these systems is an accumulation of what is termed "sludge" (or "biosolids").

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There are advantages and disadvantages to all of the above disposal options, and each has its place. However, by far the simplest and most economical method for the disposal of sludge is simply to bury it as close as possible to the removal site. Burial deals with the problems of odour and insects,

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and protects people from accidental contact with the pathogens in the sludge. Furthermore the nutrients in the sludge can potentially act as fertilizer for crops (e.g. sugarcane, fruit trees or timber). The possible risk is that the nitrates and phosphates in the sludge will leach into the groundwater and thus impact negatively on the environment in the vicinity of the burial site. There might also be a concern that the pathogens in the sludge will remain active and will pose a long term risk if the sludge is later dug up.

The purpose of this study is to go some way to answering the following questions:

- Has this method of sludge disposal been tried before?
- What is the fate of pathogens which are buried in the ground?
- How does sludge change after it is buried in the ground?
- What is the fate of the nutrients in the sludge after it is buried in the ground?
- How should one go about burying sludge in the ground and what will this cost?
- Can one make use of the nutrients in the buried sludge, and what might such use be worth?
- What are the alternatives to this method of sludge disposal, and what do such methods cost?
- If one wishes to use this method for sludge disposal, how should one go about acquiring authorisation from the relevant authorities?

Box 1: Characterisation of wastewater treatment works sludge

In 2009 the WRC published a series of five volumes by Herselman and Snyman dealing with the utilisation and disposal of wastewater treatment works sludge. In particular Volume 3 dealt with *Requirements for the On-site and Off-site Disposal of Sludge* and Volume 5 dealt *with Requirements for the Beneficial Use of Sludge at High Loading Rates*. While these guidelines were not written for faecal sludges from pit latrines, it is nevertheless helpful to have an understanding of these guidelines, which provide a frame of reference for dealing with sludge.

Before a decision is made regarding how to dispose of or use sludge, it is essential that the sludge is analysed to determine the potential dangers associated with it and what precautions to take in its use. Standard analyses will include:

1. Microbial parameters (Microbial Classes A, B, C) – includes faecal coliforms and number of viable helminth ova per unit volume.
2. Physical and stability indicators (Stability Classes 1, 2, 3) – this includes pH, Total Solids (TS), Volatile Solids (VS) and Volatile Fatty Acids (VFA).
3. Chemical characteristics (Pollutant Class a, b, c) – Nutrients, metals, organic pollutants, i.e. Total Kjeldahl Nitrogen (TKN), Total Phosphates (TP), Potassium (K) and organic pollutants (Poly-aromatic Hydrocarbons).

Sludge is thus classified in terms of a combination of Microbial Class, Stability Class and Pollutant Class. Class A1a would therefore contain the least number of pathogens, be the most stable and contain the least concentration of pollutants. Class C3c would be the most hazardous. Stabilisation (odour) is the single biggest factor that influences public perceptions of sludge.

Pollutant Class "a" means that sludge quality falls in the top 20 % in terms of South African metal quality and "c" means that it is in the bottom 20 %, i.e. compared to the average metal content in South African sludge. The main 8 metals of concern are Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg), Nickel (Ni) and Zinc (Zn).

One also has to be aware of what kind of industries are contributing to the sludge stream so that more specific analysis can be done, where appropriate. Tests for poly-aromatic carbons, in particular, need to be performed where the plant receives industrial effluent.

Part 7 of Volume 1 of the *Guidelines for Utilisation and Disposal of Wastewater Sludge* (Selection of Management Options), lists appropriate management options for WWTW sludge, which all depend on the classification of the sludge in question. The document lists detailed restrictions, depending on the class of sludge in question. In general, only sludge of Microbial Classes A or B, Stability Classes 1 or 2 and Pollutant Classes "a" or "b" should be used for agricultural use at agronomic rates or for making of compost. However, the use to which the compost will be put is very important. If it is to be used for growing of trees or rehabilitation of land, one can be less restrictive, but if it is for compost that is to be sold to the general public or for cultivation of food crops, such as leafy vegetables or plants with edible underground parts, controls have to be stringent and due care must be taken to ensure that no pathogens remain in the final product.

2. A BRIEF HISTORY OF SLUDGE ENTRENCHMENT

In 1971, the Blue Plains wastewater facility which served two million people in the Metropolitan Washington, DC area was treating approximately one million cubic meters (1 000 Mℓ) of wastewater per day and generating 200-300 tonnes of digested sludge per day (representing 40 to 60 tonnes of solids) (Walker, 1975). With the passage of the Clean Water Act in 1972, the facility was required to reduce the solids in the effluent it discharged. In response, the US Department of Agriculture, in collaboration with the Environmental Protection Agency, the Maryland Environmental Service and a number of other agencies, launched a cooperative effort to find an environmentally acceptable option for sewage sludge disposal that would also benefit soil and crops. Walker (1975) provides comprehensive documentation of the methodology used and the detailed analyses conducted on all aspects of the study.

Sludge was hauled to the site and dumped in trenches dug along the contour using dump trucks and front end loaders. In addition to sludge leaking from the trucks during transit, depositing of sludge at the site resulted in considerable surface contamination and contamination of the wheels and mud flaps of the trucks, which then tracked sludge back onto the roads. Temporary storage pits were dug on site to attempt to alleviate this problem but this gave rise to a new set of problems. The researchers recommended using a cement mixer or pump in order to pipe the sludge directly into the trenches to avoid the risk of contact with the surface.

Three different sludges were used and applied to trenches as follows:

- Dewatered digested sludge (20-25% solids) was applied at 800 dry metric tonnes/hectare to trenches 600 mm wide x 600 mm deep with a 600 mm space between trenches; 1150 dry metric tonnes/hectare were applied to trenches 600 mm wide x 1.2 m deep with a 1.2 m space between trenches.
- Undigested (raw limed) dewatered sludge (18-25% solids) was applied at the same application rates: 800 dry metric tonnes/hectare to the 600 mm deep trenches and 1150 dry metric tonnes/hectare to the 1.2 m trenches.
- Undigested (raw limed) liquid sludge (5-8% solids) was discharged pneumatically from a tanker truck into trenches 600 mm wide x 1.2 m deep with a spacing of 2.4-3.2 m between trenches. A wider distance between trenches was used for this application because of the tendency of the sandy soils to collapse into the trenches. In addition, it was found that trenches could only be filled halfway with liquid sludge or it would overflow when the trenches were backfilled; this restricted the application rate to 125 dry metric tonnes/hectare.

Trenches were typically ten percent overfilled after which they were backfilled as the trencher dug the next trench. A variety of surface treatments were trialled: plots were either left in ridges, levelled and disked or levelled, disked and cross-ripped. Levelling left a 280-350 mm soil covering above the sludge and ground surface. This soil covering was limed and either fertilised or treated with digested sludge at 35-60 dry metric tonnes/hectare in order to establish a crop. It was found that while leaving rows ridged until planting reduced erosion, it was difficult to establish ground cover on ridges. Cross ripping at right angles to the trenches did not appear to aid plant growth.

Fescue grass, maize, soybeans and alfalfa, as well as fruit and shade trees, were grown on the site. It was difficult to plant crops over the liquid sludge application because conditions in the rows remained wet and unstable. Crops performed best where sludge was shallower and trenches were closest together, with the poorest growth on the trenches filled with liquid sludge with trenches spaced furthest apart. Initially the growth of maize appeared to be inhibited by insufficient oxygen and excessive ammonia, as well as volatile compounds. This did not impact the fescue grass, however. Irrigation of the site was necessary during the course of the two year trial.

Drain lines and diversion ditches were installed to carry surface and groundwater to a 0.4 hectare drainage pond for monitoring. Forty test wells were drilled to monitor groundwater at and adjacent to the site. Chloride and nitrate levels increased in groundwater, with chloride peaking at 18 months and nitrate a year later; both decreased after peaking but at 4 years neither had returned to background levels (Sikora, 1978). While the sandy soil of the site provided conditions of extreme porosity for testing the movement of the pollutants through the soil, a clay layer beneath the sandy soil may have created a barrier which slowed movement. Movement of nitrate-nitrogen was detected from the 1.2 m raw liquid sludge trench, where close contact with the soil created unfavourable conditions for denitrification and promoted rapid conversion of nitrogen to mobile nitrate (Walker, 1975). In contrast, little nitrogen movement was found from the 1.2 m trench filled with digested sludge, which at 18 months had dewatered less than the shallower trenches or trenches filled with raw sludge. Denitrification occurred most significantly under the 600 mm deep raw limed dewatered sludge, which contained a high percentage of organic material.

Raising the pH of the sludge to over 11.5 by liming dramatically decreased the numbers of salmonella and faecal coliforms present in the sludge (Walker, 1975). However, several months after entrenchment the sludge pH dropped and numbers increased again temporarily, eventually decreasing over time. Salmonella persisted for less than 10 months. Low levels of total and faecal coliforms were still found in the soil more than two years after burial. Movement of faecal coliform or salmonella out of the sludge into the surrounding soil or groundwater was found only a few centimetres from the entrenched sludge, however. The sludge was not monitored for viruses as none had been detected in the sludge during testing prior to burial.

No downward movement of heavy metals was detected. Low concentrations of metals were taken up by plants during the study, although it appeared that these may become increasingly available to plants over time. It appeared that the higher pH in the entrenched sludge may have rendered metals insoluble, while phosphates and organic matter in the sludge may have sequestered metals, limiting movement of metals out of the trench.

2.1 Trial of sludge entrenchment for forestry, Maryland USA, 1983

In the early 1980s ERCO, Inc., a sand and gravel mining company in Maryland, pioneered the use of sludge entrenchment as a means of beneficiation for the forestry industry and for wildlife habitat creation. Hybrid poplar, which has a high nitrogen demand, was planted on land which had been mined for gravel (Kays et al., 1997). Rows 760 mm deep and approximately 1 m wide were prepared approximately 2.5 m apart from their centres. The sludge averaged about 20 percent solids, had a pH of 7.0-8.0 and a nitrogen content averaging 3.32 % before application. In the later part of the study (from 1992) sludge was required by law to be stabilised with lime before application, which reduced the nitrogen to 1.5-2.5 percent. Sludge was applied at 460 mm depth to the rows for an application rate of 382 dry tonnes per hectare and a special demonstration plot was treated with 560 mm sludge for a rate of 660 dry tonnes per hectare. The remaining 200-300 mm was filled with soil that had been removed from the trench and treated to maintain a pH of 6.2. The trenches were levelled and disked in preparation for planting.

Stem cuttings from hybrid poplar trees were planted densely over approximately 40 hectares. High density planting was chosen in order to accommodate tree mortality and quickly utilize the sludge. Tree growth remained steady but slow throughout the experiment, rather than dropping significantly after a few years as expected, and diameters were too small for the trees to be of commercial value, possibly because planting density was too high. The reduction of nitrogen levels to 1.5-2.5 percent through mandatory lime stabilization later in the study may have resulted in inadequate nitrogen levels, requiring higher application rates.

Nitrogen mineralization was assessed annually using composite samples from three depths and the utilization and fate of phosphorus was studied (Kays et al., 1997). According to regulations trees could only be harvested once foliar nitrogen dropped below 3.5 percent and total nitrogen mineralization reached approximately 70 percent. When the trees were actively growing, foliar nitrogen measured over 3.5 percent; 6 to 9 years after planting nitrogen levels in the sludge had reduced to 2.3 percent, indicating that much of the sludge had mineralised. Nitrogen levels averaged 0.02 percent only 15 cm either side of the entrenched sludge and 0.04 percent below it. Visual assessments of root growth patterns indicated that at three years after planting roots surrounded the entrenched sludge but did not penetrate it; after six years roots were found throughout the buried sludge with a large root mass around the entrenched sludge appearing to act as a sink, taking up nitrogen as soon as it was mineralized and minimising leaching.

After harvest, the trees were wet chipped. At the beginning of the study chips were used as mulch on site and were mixed into the soil during the next sludge application. Because of the high carbon/nitrogen ratio, woodchips could serve as a sink for any available nitrogen, reducing the risk of nitrogen leaching from the site. (Gouin in Kays, 1999).

While the site had been massively eroded at the beginning of the study, after repeated rotations of sludge entrenchment it was restored to a stable forested habitat with abundant wildlife.

Over 13 years, groundwater sampled from 7 monitoring wells showed no elevation in levels of nutrients, pH, metals, or pathogens. The clay soil beneath the sludge may have assisted in preventing movement of potential pollutants through the soil.

From 2001, the University of Maryland and the Washington Suburban Sanitary Commission partnered with ERCO to investigate in greater depth the effect of the planting density and sludge application rates on water quality, plant growth and economic viability described by Kays et al. (2007). In 2002, a new study was commenced on a 1.3 ha plot at the ERCO test site. The plot was partitioned into three blocks, each of which contained various application rate/tree density combinations. Thirty treatments were designed combining three different tree density rates (0, 717, 1063 trees/ha) with three different sludge application rates (11900, 23800, 35800 kg N/ha); three replicates and three control treatments (no sludge, no trees) were also included in the design. The outer two rows of trees around the perimeter of each treatment were used as buffers and samples were collected only from the innermost 16 trees in each treatment in order to reduce the possibility of edge effects. The three sludge application rates were assigned randomly within each block, while tree densities were not randomised because of logistical considerations.

Groundwater was monitored with a zero-tension pan lysimeter placed 305 mm directly below the bottom of a deep row at the centre of each treatment, suction lysimeters placed at 150 mm, 300 mm, and 610 mm below the sludge and at 150 mm and 300 mm from the sides of sludge, and seven groundwater monitoring wells installed at depths ranging from 7.6 m to 39 m. Entrenched sludge did not impact on the groundwater at two years into the study. In fact, no migration of nitrate to groundwater was found at the site throughout the course of the entrenchment studies conducted at the site from 1983 to 2005. Kays et al. (2007) found that at these application rates nitrate was not released from the sludge to the environment during the first two years, and while ammonium did leach from the trench, it quickly became bound in the soil and in this study did not travel further than 600mm. After two years it appeared that the trees were just beginning to access the sludge, and foliar nitrogen and phosphorous levels were similar to fertilized trees. Subsoiling prior to planting appeared to provide a number of benefits: shorter crop rotation length might be possible due to saplings establishing themselves more quickly in less compacted soil, lower mortality and higher growth despite more severe browsing by deer. A study of the economic potential of sludge application indicated little gain for the 23,800 kg N/ha rate, but substantial economic gains at higher application rates despite greater costs for application.

2.2 Sludge entrenchment in Philadelphia, US, 2005

Since the late 1970s, the Philadelphia Water Department has used more than 1 million tonnes of sludge for the reclamation of approximately 2 000 hectares of mine lands. The conventional method of application over these three decades for mine reclamation has been the surface application of dewatered sludge at rates of up to 134 dry tonnes/ha using manure spreading equipment followed by plowing to attempt to incorporate the sludge into the top 150-300 mm of soil then planting with eucalyptus and grasses.

In 2005, sludge entrenchment was tested for the reclamation of a coal mine (Toffey, Flamino, Pepperman et al., 2007). An area of 5,6 ha was prepared with two control plots on which no sludge was entrenched and three treatments were tested of 134, 160 and 224 dry tonnes per hectare. Lime was added at approximately 11 tonnes /ha, and the area was planted with hybrid poplars.

By the end of the second growing season, trees planted on the 224 t/ha treatment were on average 2 to 3 times higher and nearly 10 times heavier than the control group. Planting on or between rows yielded the same growth rates. Trees in the 224 t/ha treatment had more extensive root systems, with the largest roots growing in the direction of the sludge. Foliar sampling showed higher nutrient levels with the capacity to utilise additional nitrogen. Monitoring of pathogens showed that die off continued and there was no evidence of regrowth a year after entrenchment. Nitrogen mobilisation out of the trench was slowed by the high demand of the trees and the anaerobic conditions and cooler temperatures which slowed microbial activity in the trench. Researchers calculated that, with generation of $C0_2$ by equipment used in entrenchment considered, approximately one tonne of CO_2 equivalents was sequestered per wet tonne of sludge through the growth of the trees and increase of carbon in the soil.

2.3 Discussion

Based on the experience recounted above, utilisation of sludge through surface application, shallow incorporation and sludge entrenchment all demonstrate benefits to vegetation and improvement of soil. The potential benefits for entrenchment are the following:

- Far greater quantities of sludge can be applied, reducing the frequency of application and thereby reducing costs and risks of contamination.
- Entrenchment improves the structure and organic content of soil more intensively and, when used to rehabilitate soils, shows the potential to restore the capacity of land to support vegetation and wildlife.
- With surface application, aerobic soil microbes rapidly convert organic nitrogen to ammonia and nitrate nitrogen, releasing most of the nitrogen present in sludge over the first three years. With entrenchment, sludge is held in anaerobic conditions in the trench until tree roots slowly begin to penetrate the sludge and introduce oxygen. Cooler temperatures and lack of oxygen in the trenches slow microbial activity. This results in nutrients being released from the sludge at a slow rate, which both sustains the provision of nutrients to the tree for the duration of a 6-8 year rotation and slows the rate at which nitrates leach into the soil, reducing the risk of surface or groundwater contamination (Toffey 2007), and saving costs in terms of frequency of application.
- As sludge is not available on the surface, it will not promote forest floor vegetation which could inhibit the growth of young trees.
- In terms of safety, while sludge applied by other methods will be restricted based on the stability and microbiological risk of the sludge, entrenchment is applicable for pit sludge and wastewater sludge unless it falls into Pollutant class ***c***.
- In terms of stability, burial of sludge represents a vector reduction placing the sludge out of reach of vectors and eliminating the issues of odours (with the exception of the period during the entrenchment process itself), making entrenchment an option for all stability classes. This can also allow for smaller buffer zones between the area of application and human settlements.
- In terms of microbiological risks, burial also dramatically reduces the risk of contact with pathogens, making entrenchment an option for all microbiological classes. If protocols are followed carefully to prevent contamination of the environs during entrenchment, pathogens which pose a risk to humans and animals will not be present on the surface. No restrictions on animal grazing are therefore needed. Findings of research into pathogen survival after entrenchment at 2.5 years indicate significant die off, suggesting that when workers disturb the site at harvest at (typically after 8 to 10 years, there will not be a risk of infection.
- In terms of pollutant classes, entrenchment should be acceptable for all domestic faecal sludges and for class ***a*** and ***b*** wastewater sludge if, in combination with the pollutant content of the receiving soil, it does not exceed the maximum burden allowed. The slow release of pollutants held in the sludge when entrenched also assists with controlling the risk of surface or groundwater contamination.

A final consideration is the presence of detritus which is typical of pit sludge in South Africa and has proven highly problematic in both the removal of sludge from pits and its disposal. While the presence of rubbish in sludge would obviously limit its potential for surface application or shallow incorporation, with entrenchment it can simply be buried without being extracted from the sludge with no harm to crops.

Although the research that has been conducted to date on sludge entrenchment has shown positive results, it was considered appropriate to run similar trials in South Africa to see if the results could be replicated. While the Maryland and Philadelphia trials have focussed exclusively on the entrenchment of treated sludges from wastewater treatment works, in the South African context the VIP pit latrine is the norm for basic sanitation provision. Therefore it was of relevance to investigate entrenchment as an option for the beneficial use of sludge derived from pit latrines as well as that from wastewater treatment works.

3. DESCRIPTION OF FIELD TRIALS

3.1 Introduction

To date five sludge burial/entrenchment trials of varying scale have been conducted. The first, at Inadi just outside Pietermaritzburg, involved just two families and was useful to get an indication of practicalities as well as the potential response from those involved in either the emptying or the use of the sludge. The second was carried out at the University of KwaZulu-Natal and entailed the planting of 24 trees in 750 mm diameter concrete columns, with 12 controls without sludge and 12 experimental columns which included a core of sludge surrounded by soil. The third was carried out in conjunction with the eThekwini Metropolitan Municipality which was emptying VIP pits in Umlazi at the time. Approximately 1200 m^3 of this sludge was buried in deep trenches on the flat sandy site of an old oxidation pond. Eucalyptus and wattle trees were planted on the site and a number of boreholes were sunk for monitoring the groundwater. The fourth trial has involved the entrenchment of approximately 360 m^3 of secondary wastewater treatment works sludge from the midlands town of Howick in a forestry plantation belonging to the forestry company Sappi on sloping ground with shallow soil. The fifth and final trial is being conducted on sloping ground at the back of the property belonging to Partners in Development (PID) in Pietermaritzburg. In this trial the focus is on very close monitoring of leachates in the immediate vicinity of the buried sludge. The first four trials have all been described at greater length in the report on the previous phase of this project (Still et al., 2012), but are summarised here for ease of reference. Work on the Umlazi and Sappi trials has continued in this phase, while the leachate monitoring at PID is new.

3.2 Burial of pit latrine waste at Inadi, Pietermaritzburg

A small trial was initiated in August 2007 to investigate the possibility of using on-site burial of sludge to provide nutrients to fruit trees on the same plot where the sludge was removed. Two homeowners willing to participate in the study were identified in the Inadi area northwest of Pietermaritzburg. Each had a pit which had filled and was no longer in use.

The two disused pits were emptied manually by the homeowners themselves, who expressed no unwillingness to perform this task. Both pits were reported to have been full when they were closed and homeowners reported that only a 300-400 mm covering of earth had been required to fill in the pit to ground level. As the volume of sludge had decreased as a result of degradation over time, the first household had added more soil to fill the depression, while the second household had added garden waste. When the pits were emptied, faecal sludge was only encountered at a depth of 1.65 m at the first household and 1.15 m at the second household. Subsequent work with sludge burial has borne out this experience: with moisture reduction and ongoing sludge decomposition, the volume occupied by buried sludge typically decreases by 50% or more over a period of years.

The sludge comprised two distinct components. One was a dryer, peaty, black, odourless fraction that appeared to be well stabilised; the second was a wetter, more “fresh” looking fraction with a strong unpleasant smell. The peaty fraction was found in contact with soil whereas the malodorous fraction was found in clumps of non-biodegradable material, particularly plastic bags. Initially, the pit sludge seemed to contain a considerable quantity of non-biodegradable matter (plastic bags, cloth, bottles, etc.). However, when separated the volume of this material amounted to only 0.08 m^3 (8%) for the pit at the first household and 0.18 m^3 (14%) for the pit at the second household. This non-biodegradable material was later reburied.

Figure 3.1 Manual excavation of a pit. The start of the sludge layer is clearly visible 1.65m below the surface.

3.2.1 Tree planting and sludge application

Holes were prepared for the fruit trees approximately 900 mm square and deep. The two homeowners were offered any three fruit tree varieties of their choice. The first homeowner selected three orange, three mandarin and three lemon trees. Each of the three trees of the same species received one of three treatments:

1. 315 ℓ sludge layered in 90 ℓ batches with soil and mixed with a garden fork.
2. A handful (approximately 40 g) of superphosphate scattered around the base of each tree and worked in superficially with a fork.
3. Tree planted in only the soil that had come from the hole (control)

It was ensured that no sludge was incorporated into the top 300mm of soil around each tree. The owners were asked to subsequently treat all trees identically with regard to watering and weeding.

The second household selected two peach and four orange trees, each of which received one of the following treatments:

1. A handful (approximately 40 g) of superphosphate scattered around the base of each tree and worked in superficially with a fork.
2. 240 ℓ sludge layered with soil and mixed with a garden fork.
3. 320 ℓ sludge layered with soil and mixed with a garden fork.

3.2.2 Results

Until mid-2011, the trees grew well, with only one mortality of the 15 planted. Table 3.1 shows the record of the growth of the trees from planting in August 2007 until August 2011. While the number of trees in the study was too small for data to be statistically significant, the increase from height at planting did reflect the trend of trees showing the least increase with no treatment and increasing benefit with 40 g super phosphate, 240 ℓ sludge and 315-320 ℓ sludge, with the exception of the mandarin trees, which showed a far higher increase in the growth of the tree which received no treatment. The reason for this is not known, but because the growth of the trees treated with superphosphate and sludge was significantly lower it is possible that these two trees experienced a set back which compromised their growth, such as disease or pests.

Figure 3.2 Orange trees planted from top left in, respectively, soil mixed with sludge, soil with 40 g super phosphate and soil only.

A foliar nutrient analysis conducted on trees at approximately 3.3 years after planting did not show consistent trends for trees with no sludge, super phosphate or sludge.

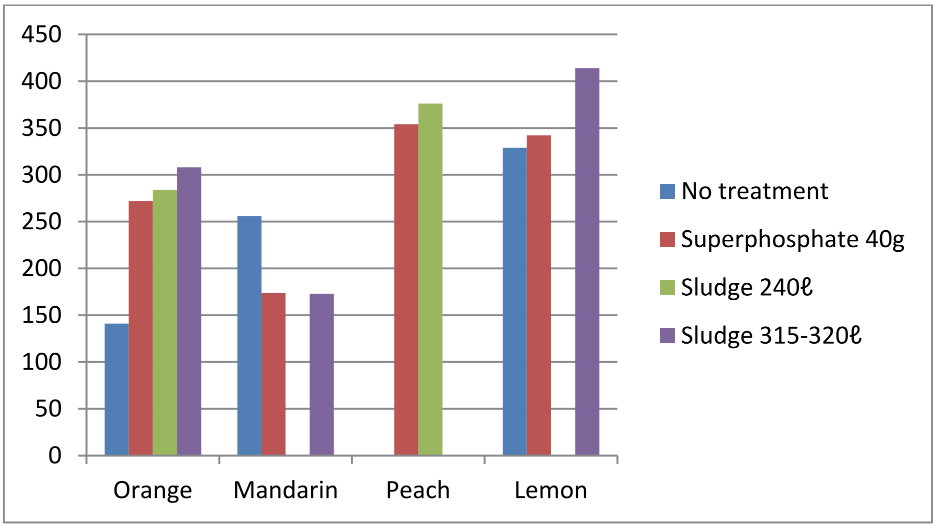


Figure 3.3 Increase in growth (%) of fruit trees with different treatments from time of planting to 4 years after planting

Homeowners reported that the trees produced excellent fruit and that neighbours had inquired about using the same methods. During the second half of 2011 however several of the citrus trees were diagnosed with greening disease (a serious disease endemic to citrus in this region) and all symptomatic branches on all trees were removed. With up to 50% of branches removed, it was not possible to gather further meaningful data comparing the growth and nutrients levels of trees from this study.

Table 3.1 Comparison of increase in height for Inadi fruit trees planted on sludge enhanced soil vs those planted on ordinary soil over 4 years

Variety	Treatment		Tree height (in metres)			
	Sludge	S Phosphate	23/8/07	25/8/11	Growth	(% increase)
Orange Z	-	-	0.96	1.35	0.39	41
Orange Z	-	40 g	0.85	dead	dead	
Orange K	-	40 g	0.9	2.45	1.55	172
Orange K	240 ℓ	-	0.95	2.7	1.75	184
Orange Z	315 ℓ	-	0.95	2.6	1.65	173
Orange K	320 ℓ	-	0.88	2.8	1.92	218
Orange K	320 ℓ	-	0.6	1.97	1.37	232
Mandarin K	-	-	0.76	1.95	1.19	156
Mandarin K	-	40 g	0.69	1.2	0.51	74
Mandarin K	315 ℓ	-	0.75	1.3	0.55	73
Peach K	-	40 g	1.27	4.5	3.23	254
Peach K	240 ℓ	-	1.3	4.9	3.6	276
Lemon Z	-	-	0.76	2.5	1.77	229
Lemon Z		40 g	0.76	2.6	1.84	242
Lemon Z	315 ℓ		0.69	2.86	2.17	314

Because the number of trees in this study was too small for data to be statistically significant or for observations or possible effects to be substantiated, it would be useful for a larger, more controlled study to be conducted to investigate more thoroughly the benefit of sludge to fruit trees which could represent a significant contribution to food security for families with onsite sanitation.

3.3 Controlled tree tower study at UKZN[2]

In order to investigate the impact of pit latrine sludge on tree growth under more controlled conditions, a study was conducted in which *acacia mearnsii* (wattle) and *eucalyptus grandis* were grown in pots containing a core of faecal sludge surrounded by a sandy soil. The study explored the ability of sludge to aid plant growth in comparison with fertiliser for both species and assessed the impact of sludge on photosynthetic parameters and spatial root distribution.

[2] The work described in this section was carried out in 2009 by Craig Taylor in fulfilment of the requirements for his Master's Thesis for the School of Biological Sciences, UKZN

3.3.1 Preparation of the site

Twenty-four planting containers were constructed by stacking four concrete manhole rings on a concrete base, creating a 1m high structure with an internal diameter of 750 mm. A layer of PVC sheeting was partially embedded in the base of each column to prevent seepage into the base, with a channel exiting the column to allow drainage. The joints between the manhole rings were sealed.

Figure 3.4 Experimental tree tower site at UKZN (Howard campus)

3.3.2 Sludge application

A 250 mm base layer of river sand was placed in each of the 24 columns. Faecal sludge was removed from full pit latrines, transported in 100 litre bins and placed in the columns the same day. For the 12 experimental columns, a 450 mm diameter polycarbonate cylinder was placed in the centre of each base layer of sand and filled with sludge to an approximate height of 500 mm above the base layer (see Figure 3.5). This created a core of sludge faecal sludge 500 mm in height and 450 mm in diameter, with a volume of 0.22 m^3. The area around the cylinder was filled with sand, creating an annulus approximately 150 mm in width. The core of sludge was covered with a 250 mm layer of river sand.

The remaining 12 columns were not treated with any faecal sludge but were filled with river sand to the same height as the columns in the treatment group (approximately 1 m). Throughout the experiment these columns were treated with fertiliser so as to serve as a positive control in the experiment.

3.3.3 Tree planting and maintenance

Trees were planted in the columns the day after the columns were prepared. Eucalyptus (*eucalyptus grandis*) and wattle (*acacia mearnsii*) were selected because they are fast-growing and are commercially grown as a source of timber. *Acacia mearnsii* has been found to show a significant growth response to applications of phosphorus and potassium, but less response to nitrogen applications because of its ability to fix atmospheric nitrogen. Eucalyptus responds well to fertiliser, growing as high as 20 m in 3 years under favourable conditions. In the 12 experimental columns containing a core of faecal sludge, 6 seedlings of each species were planted. In the 12 control columns, 6 seedlings of each species were planted. These were bedded in 300 mℓ of compost to improve water retention and provide nutrients for early seedling establishment, which may have proven problematic in sand.

Figure 3.5 A polycarbonate cylinder (left) was used to fill the tower with a core of sludge ringed by river sand (right)

Plants in the experimental group were irrigated immediately after planting with 1 ℓ of water and were watered as needed thereafter. Plants in the control group received 1 ℓ of a 1 g/ℓ aqueous fertilizer after planting and biweekly thereafter, alternating with a 2.5 mℓ/ℓ aqueous trace element solution applied alternate weeks. Plants in the control group were irrigated with the same quantities of water and at the same times as plants in the experimental group throughout the experiment. No herbicides or other chemical treatments were used on the columns during the experiment. Aphids were removed by spraying with water and the columns were weeded weekly.

At approximately two months, all wattle seedlings were staked with bamboo to prevent lodging. Trees were harvested at approximately 6 months (26 weeks) after planting.

3.3.4 Results

Analyses were completed of sand, sludge and plant tissue samples. Plants were monitored for growth, chemical and physical change and gas exchange. Plant height was measured after planting and thereafter every second week. Stem diameter was measured every month. Photosynthetic measurements were taken on expanding young leaves of both species when plants were approximately six months old. Measurements of assimilation, intercellular CO_2, stomatal conductance and transpiration were taken. Soil and leachate quality were monitored.

At harvest, tree trunks were cut as close to the base of the stems as possible. Twigs were cut from the trees and leaves were separated from the twigs. Dry biomass was determined using a 200 g sample of each component (leaf, twig or trunk) which was then air dried to constant weight after which a 100 g sample of each was oven dried. Total leaf area was estimated by determining the ratio of leaf area per unit leaf mass of a 50 g sample for each replicate. Root distribution was analysed after the towers were dismantled.

Height

For eucalyptus, difference in height between the experimental and control groups became apparent by the ninth week. By the end of the study at 26 weeks, the mean height of the experimental group was approximately 2.3 times greater than that of the control group (244 cm and 108 cm respectively). While tree height levelled off soon after the midpoint of the study, mean root collar diameter increased throughout the period of the study. At 26 weeks, mean root collar diameter measured at 40 mm for the experimental group and 34 mm for the control group -- a relatively small difference in comparison with the considerable differences observed in tree height, indicating that biomass was preferentially partitioned into stem diameter rather than stem length in the control group.

For wattle, however, differences in mean height between the experimental group (270 cm) and control group (232 cm) were small and differences between stem diameter at harvest were insignificant (45 mm and 39 mm).

Table 3.2 Growth data for experimental and control groups of both species

Parameter	Eucalyptus		Wattle	
	Experimental	**Control**	**Experimental**	**Control**
Height	244 cm	108 cm	270 cm	232 cm
Root collar diameter	40 mm	34 mm	45 mm	39 mm
Mean leaf area	11.97 m2.	1.83 m^2	3.73 m2.	1.95 m2.
Specific leaf area	18.9 m2.kg-1	10.6 m^2.kg-1	5.9 m2.kg-1	4.7 m2.kg-1
Total aboveground biomass	1517 g	362 g	1558g	1038 g
Leaf biomass	42.1%	48.4%	40.7%	40.1%
Trunk biomass	22.1%	23.6%	29.4%	30.2%
Twig biomass	35.8%	28.0%	29.8%	29.7%

Mean leaf area

For eucalyptus, mean leaf area was 6.5 times greater than in the control group (11.97 m^2 vs 1.83 m^2), indicating that foliage production was severely restricted in the control group where leaves were visibly fewer in number and smaller than those of the experimental trees. Leaf area did not appear to increase visibly during the final two months of the study, suggesting growth in terms of both height and foliage production had reached a ceiling. Leaf loss, indicating reduced leaf lifespan, was evident in the control group where branches were bare of leaves closer to the trunk, probably due to nutrient stress.

For wattle, mean leaf area for the experimental group was twice that of the control group (3.73 m^2 vs 1.95 m^2), with vigorous lateral growth at the base of the trees, while leaf production for trees in the control group appeared to halt approximately one month before harvest, rather than experiencing leaf loss.

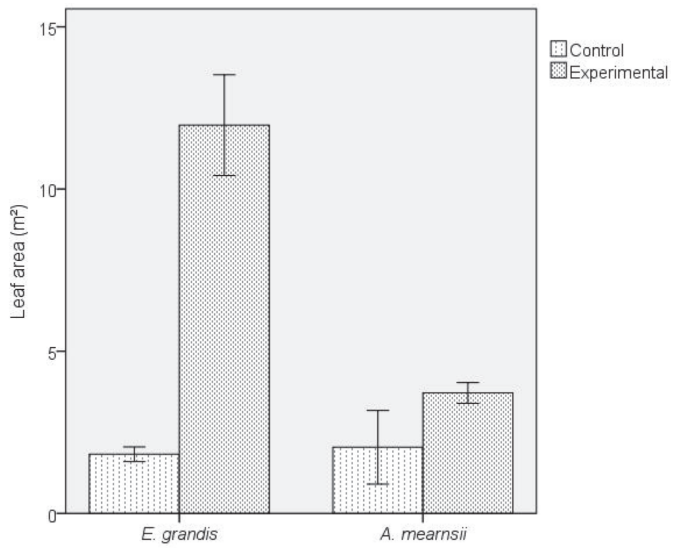


Figure 3.6 Mean leaf area of eucalyptus (left) and wattle (right)

Dry biomass partitioning

For eucalyptus, total aboveground biomass was almost four times greater in the experimental group for each of the measured components (trunk, twigs and leaves) than in the control group (1517 g vs 362 g). Leaves represented the greatest resource sink for both experimental and control groups (42.1% and 48.4%), with trunks accounting for approximately one fifth of total dry biomass (22.1% and 23.6%) and twigs roughly a third of total dry biomass (28.0% and 35.8%).

Differences between experimental and control groups were less marked for wattle (1558g vs 1038g for total aboveground biomass), with nearly identical partitioning for leaves (40.7% and 40.1%), trunk (29.4% and 30.2%) and twigs (29.8% and 29.7%).

Figure 3.7 shows the above results graphically.

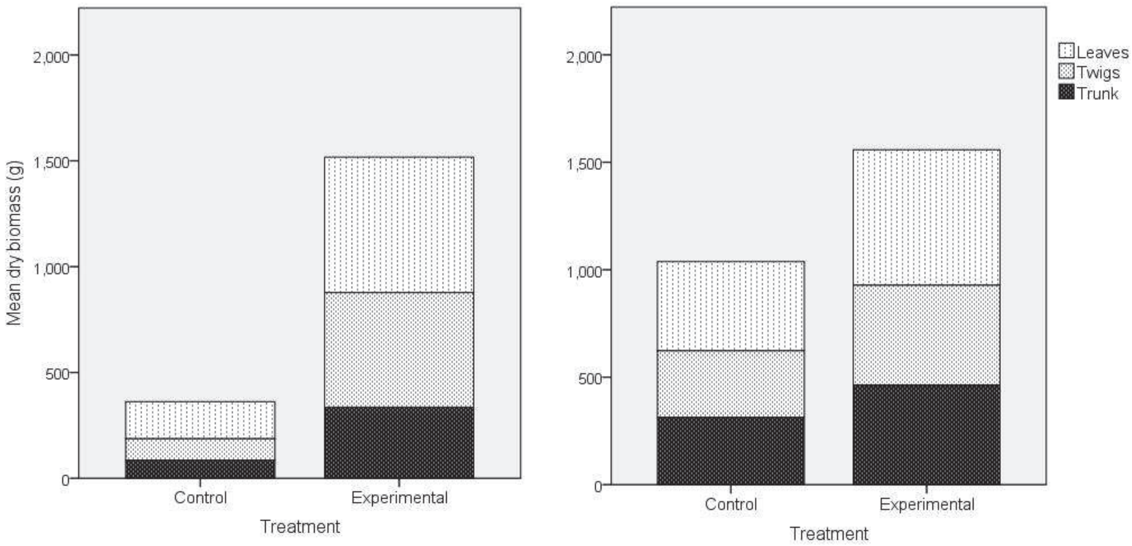


Figure 3.7 Mean dry biomass partitioning of leaves, twigs and trunk for eucalyptus (left) and wattle (right).

It is clear that the growth of both species was enhanced by the application of faecal sludge, with greater benefit to eucalyptus which does not have the nitrogen-fixing properties that support the ability of wattle to thrive in poor soil. While the control trees had received fertilizer, their growth was poorer than expected, which may be due to the porosity of the sand resulting in excessive leaching of nutrients away from tree roots. The enhanced growth in the presence of sludge observed in this study was consistent with growth observed during a 12 month study in which eucalyptus treated with sludge showed 86% greater biomass over control trees (da Silva et al., 2011).

Foliar nutrient concentrations

For eucalyptus, all primary and secondary macronutrients occurred in greater concentrations in the foliage of the experimental trees with the exception of calcium, indicating improved nutrition. Nitrogen (N) concentration in the foliage of experimental trees (329 mg.kg-1) was nearly three times greater than in control trees and phosphorus (P) (31 mg.kg-1)was approximately double. Differences in potassium (K) were less significant (105 and 72 mg.kg-1).

Deficiencies of these nutrients, in particular nitrogen, likely had the greatest limiting effect on tree growth in the control group, which exhibited lighter green foliage and purple colouration on growing tips in the latter part of the growing phase and had a lower N:P ratio (7.9) than the experimental group (11.1) For micronutrients, iron (Fe) was significantly greater in experimental trees (203 mg.kg-1 and 163 mg.kg-1) and aluminium (Al) was greater in control trees.

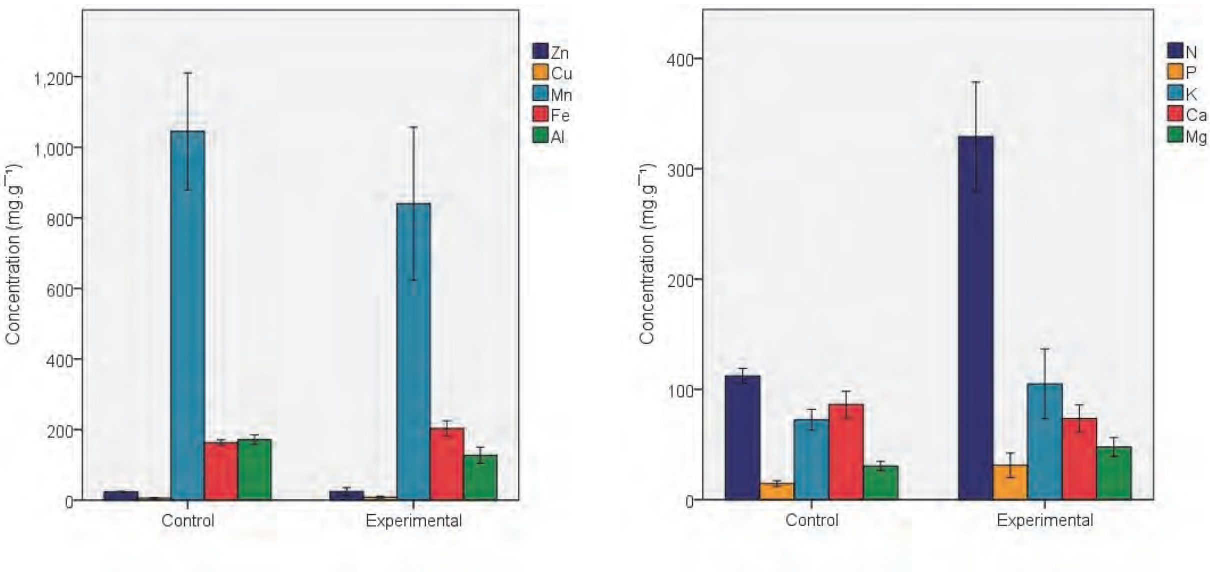


Figure 3.8 Foliar micronutrients (left) and macronutrients (right) in eucalyptus

Figure 3.9 Growing tips of *E. grandis* from trees of experimental (left) and control (right) groups at approximately 5.5 months after planting

Wattle showed similar trends, but with statistically greater concentrations in control trees than with eucalyptus. Calcium again appeared in greater concentration in control trees. Nitrogen was higher in foliage of experimental trees (319 mg.kg-1 and 233 mg.kg-1; p=0.006). The concentration of foliar phosphorus (P) in the leaves of experimental trees (45 mg.kg-1) was approximately 4.5 times greater than in control trees and potassium (K) in the experimental group (126 mg.kg-1) was approximately twice that of control trees (p<0.0005). Nitrogen (N) 319 mg.kg-1 was similar to levels in eucalyptus. A higher N:P ratio for the foliage of control trees indicates that phosphorus was more deficient than nitrogen and no visible symptoms of K deficiency were evident in control trees. Magnesium (Mg) was also higher for experimental trees (27 mg.kg-1 compared with 18 mg.kg-1). For micronutrients, Zn was statistically greater in experimental trees than control trees (18 and 26 mg.kg-1), while levels in control trees were higher for Cu, (9 and 4 mg.kg-1), iron (Fe) (258 and 179 mg.kg-1) and aluminium (Al) (169 and120 mg.kg-1).

Spatial root distribution

At the end of the study, the tree towers were dismantled and root development in the sand and at the sand/sludge interface was examined. The sludge cores for experimental towers were too dense to permit the extraction of roots from the core itself for analysis of patterns and biomass, however it was evident that root distribution was not impeded by the presence of sludge.

Figure 3.10 Root development of eucalyptus around sludge core

Fine roots were matted densely just beneath the surface for both species and also on the periphery of the sludge core in response to the higher nutrient levels and possibly also high moisture levels in the sludge. Fine roots decreased sharply with depth, which is usual in forest species. Medium and coarse roots of both species were fairly evenly distributed throughout the soil, reaching to the bottom of the towers. Medium and coarse root intersections were counted on three horizontal planes for experimental trees: above the sludge core (125 mm), through the sludge core (500 mm), and below the sludge core (625 mm). Root intersects were generally greater in the outer ring of sand for both experimental and control groups, growing laterally out to the column walls and then turning downward, with only a few coarse and medium roots below the stump, penetrating the sludge core in the case of the experimental group. In an earlier study using eucalyptus, however, Bouillet et al. (2002) documented medium root density to be greatest below the stump, suggesting that the lateral rooting in this study may have resulted from early containerised growth. This may have also prevented the development of a normal tap root system, which in both species would have promoted stronger penetration of roots into the sludge core.

A greater proportion of root intersections in both species were found to intersect the faecal sludge core at a depth of 500 mm compared to the control trees, particularly in the wattle, where 31.3% of roots at that depth had intersected the faecal sludge core while only 7.9 % of roots in the control were found in the equivalent area. This indicates that although the sludge core was likely too wet initially to have promoted root penetration, over time faecal sludge was able to support root growth and did not inhibit normal root distribution. In eucalyptus, a mean of 88 root intersects occurred in the experimental eucalyptus trees while 155 root intersects occurred in the control trees, suggesting that control trees had produced a greater root biomass in order to forage over a greater volume of soil in the nutrient poor soil. In wattle, however, the opposite occurred: a mean of 46 root intersects occurred in the control trees while 164 root intersects – representing a 357% increase – occurred in the experimental trees. The control group did, however, contain more fine roots, which assist in acquiring nutrients and water.

3.4 Entrenchment of sludge at Umlazi E ponds Burial of pit latrine waste at Umlazi, Durban

The eThekwini Metropolitan Municipality has taken a proactive approach to the challenges of emptying pits and finding appropriate options for the disposal and utilisation of sludge. eThekwini offered three sites for potential use for a sludge entrenchment study. The site of a disused wastewater works in Umlazi was selected.

3.4.1 Site description

The Umlazi site had been used as wastewater treatment works by eThekwini Municipality until heavy flooding damaged the oxidation ponds in 1987. The land is valueless for development because it is below the 1:50 year flood line. The ponds are situated on flat to gently sloping ground at the foot of a steep, densely populated hill side in the Umlazi residential zone E section. The lower edge of the site is approximately 80 m from the Umlazi River. The site is 20km south west of the city centre with an average annual rainfall of 1000 mm.

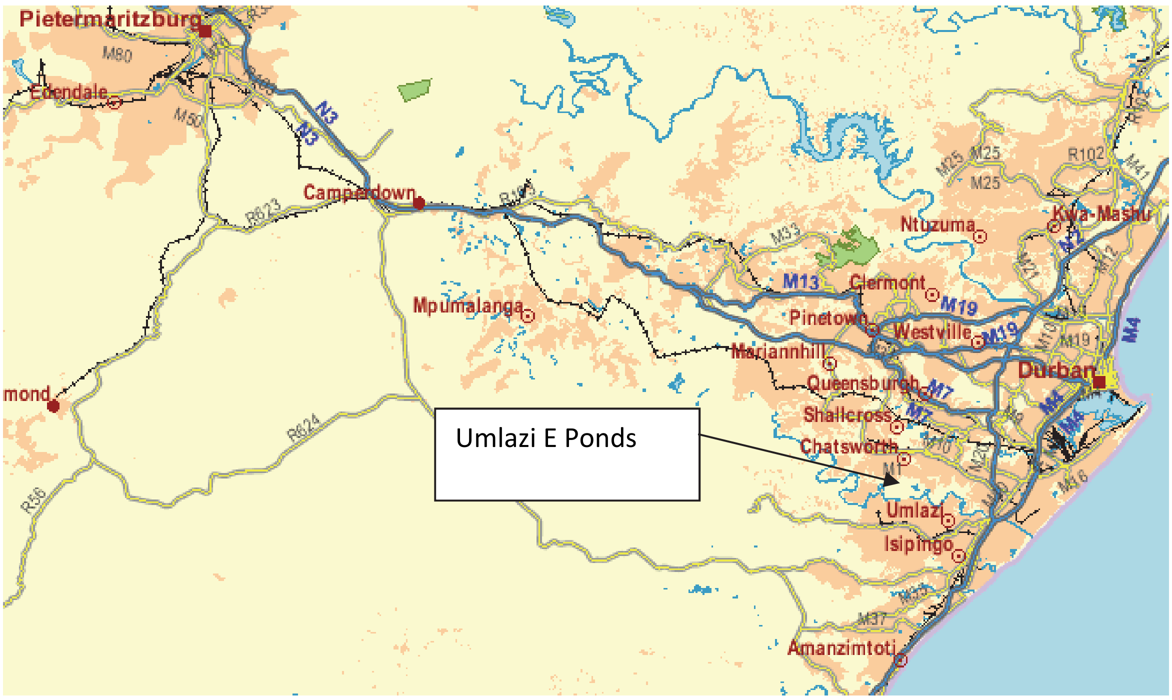


Figure 3.11. Location of Umlazi pit latrine sludge burial site

The site of the ex-pond is approximately 5 000m^2 in size with a soil profile comprising fine, silty river sand with low organic content. Trial pits were dug to a depth of two metres without encountering any change in the soil make up and without reaching the water table (although it was later discovered that the water table rose to near ground level during the wet season and additional drainage measures had to be implemented).

Because the trial site bordered residential areas of Umlazi (E section), the local councillor had to be consulted and appraised of developments on the site. Several community meetings were held to discuss the study and to obtain permission to proceed. Permission was also obtained from the Department of Water Affairs.

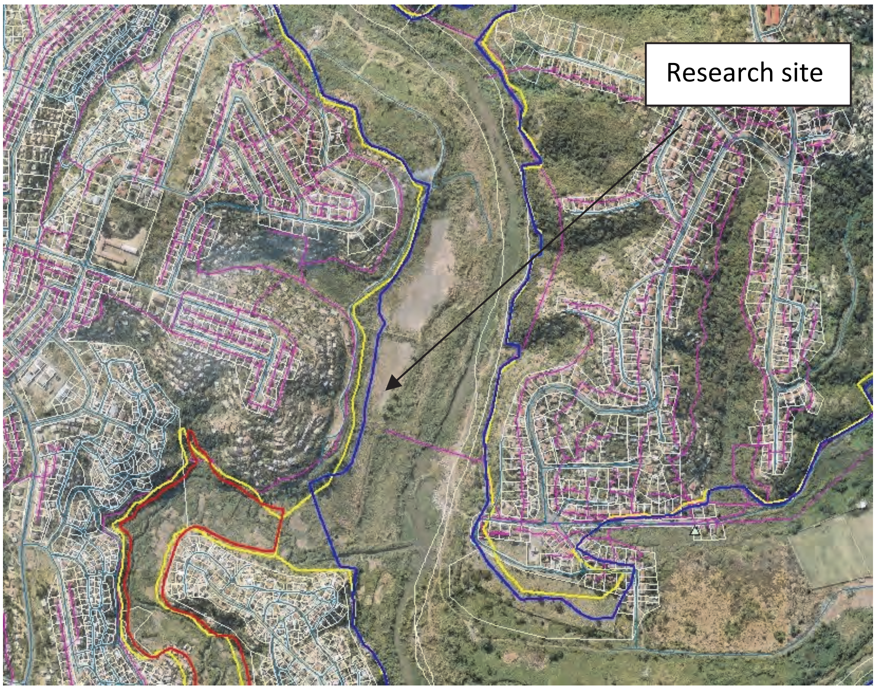


Figure 3.12 Umlazi site: 1:50 year flood line shown in blue and 1:100 year flood line in yellow

Figure 3.13 (below) Research site at the beginning of the study, cleared of vegetation, with the Umlazi river running at the foot of the hill in the background

Figure 3.14

Entrenchment of pit sludge at the Umlazi site commenced in September 2008

Sludge was buried on the site in a total of 32 rows between September 2008 and October 2009. Initially every fourth trench was refilled without sludge to act as a control, but it was soon realised that this still meant that no trees' roots were far enough from buried sludge for these controls to usefully test the "no-sludge" status. This was the more so because most of the sludge was entrenched during a wet period where the water table was higher than expected with the result that the trenches tended to collapse and ended up being wider than planned. Later a section of nine rows were planted at the northern end of the site, and only one and half rows were planted over sludge, the rest acting as a control.

Five 20 metre deep screened groundwater monitoring boreholes were established between the trenching site and the river before the commencement of the trial.

Figure 3.15 Location of borehole sites at Umlazi (BH1 to BH5). The main section of trees was used to monitor changes in sludge composition, the effect on the groundwater and the die off rate of pathogens. Only the nine rows on the northern end of the site were adequately controlled to check the effect on tree growth.

Figure 3.16 Eucalyptus trees in January 2012, three years after planting

3.4.2 Results

Tree growth

Tree growth was measured periodically over the course of the trial for wattle and eucalyptus trees in the experimental block (Rows 1- 9). For purposes of comparison, tree measurements from the following rows were used (they were all planted in October 2009).

Row 3: Sludge entrenchment

Row 4: Buffer (no treatment – roots possibly accessing sludge in Row 3)

Row 5: Control (no treatment)

Row 7: Fertiliser treatment

Row 4 was measured to monitor whether there was any effect that might suggest that the tree roots could be accessing nutrients from sludge entrenched in Row 3. Measurements gave no indication of enhanced growth in Row 4 over Row 5 (see Figures 3.17 and 3.18). From January 2011 it was no longer possible to measure tree height with any accuracy, so measurements of tree diameter taken at chest height (1.37 m) were used from this point onwards for comparison. Due to unauthorised felling of trees for firewood by individuals in the community, as well as mortality, the number of trees for each species dwindled to as few as 6 in some rows by the end of the study, with the result that comparisons were not statistically significant. The trends that were observed were informative, however. Mean values for measurements taken from 17 January 2011 (1.25 years after planting) periodically until 29 March 2012 (2.5 years after planting) are presented below for both species.

For eucalyptus, there was consistent growth for all four rows, with trees planted on entrenched sludge (Row 3) showing consistently higher growth than the buffer (Row 4), control (Row 5) or fertilizer treatment (Row 7) rows.

The advantage experienced by trees with access to sludge appeared to peak at 1.5 years after planting (April 2011) with 75% greater mean stem diameter than control trees and 30% greater stem diameter than fertiliser treatment trees. The advantage over control trees then declined to 46% greater stem diameter at approximately 2 years after planting (August 2011) and 13% at 2.5 years after planting (March 2012).

Note that biomass is proportional to the *cube* of the diameter, being a product of area (which is proportional to the square of diameter) and height (which is linearly correlated with diameter – see Figure 3.26). A difference of 13% in diameter is therefore equivalent to a difference of 45% in biomass.

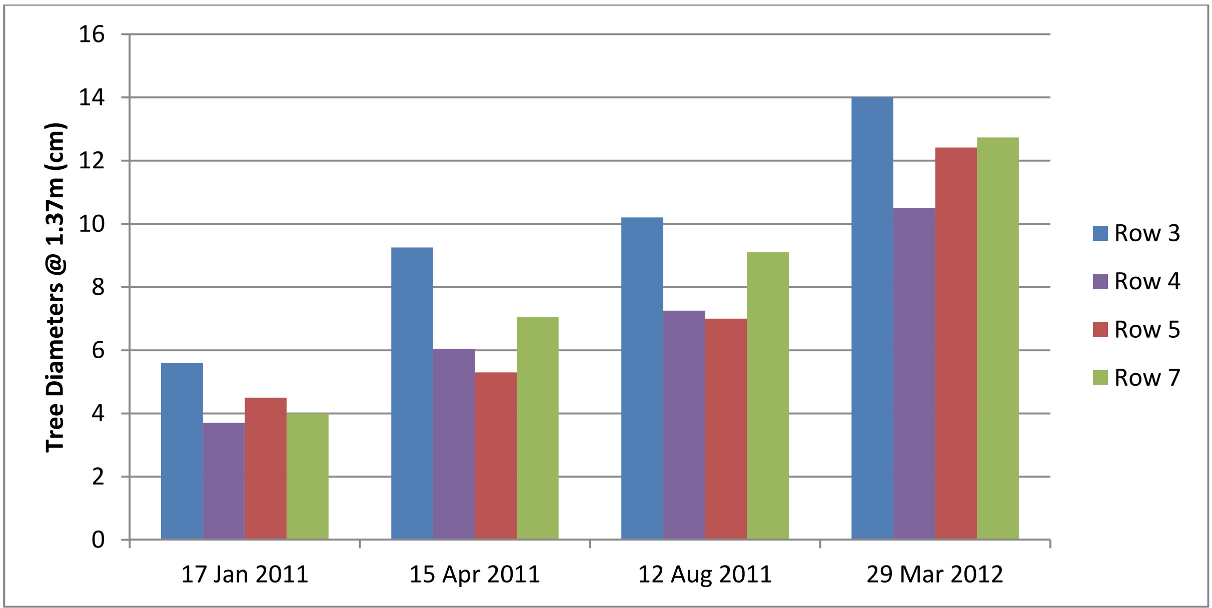


Figure 3.17 Changes in stem diameter (measured at 1.37m) for experimental eucalyptus rows over time (mean values)

Table 3.3 Mean values for stem diameters and relative gains in growth for different treatments for eucalyptus trees

	Diameter at 1.37 m			Percentage greater diameter	
Month	**Row 3: sludge**	**Row 5: control**	**Row 7: fertiliser**	**Row 3 over Row 5**	**Row 3 over Row 7**
January 2011	56 mm	45 mm	40 mm	24%	40%
April 2011	93 mm	53 mm	71 mm	75%	30%
August 2011	102 mm	70 mm	91 mm	46%	12%
March 2012	140 mm	124 mm	127 mm	13%	10%

For wattle, the effect of sludge on growth was more limited. This may have been due, in part, to the ability of wattle to fix nitrogen from the atmosphere, with the result that a lack of nitrogen in the soil would not limit growth for this species to the same extent that it would for eucalyptus.

It was expected, however, that apart from nutrient benefits the sludge would have improved the soil structure over the poor native soil and enhanced conditions for growth on that basis alone. It is unclear why, instead, growth appeared actually more limited in the sludge row than the control and fertilizer rows, with the mean diameter in the control row 18%, 38%, and then 16% greater than mean diameter in the sludge row over successive measurements. In addition, growth in the fertilized row was inferior to the control row, with trees in native soil performing the best over three sets of measurements. This may be due to some extent to variation in the native soil from one row to the next. It must be stressed, however, that the numbers of trees involved in this particular trial is too small to draw any significant conclusions.

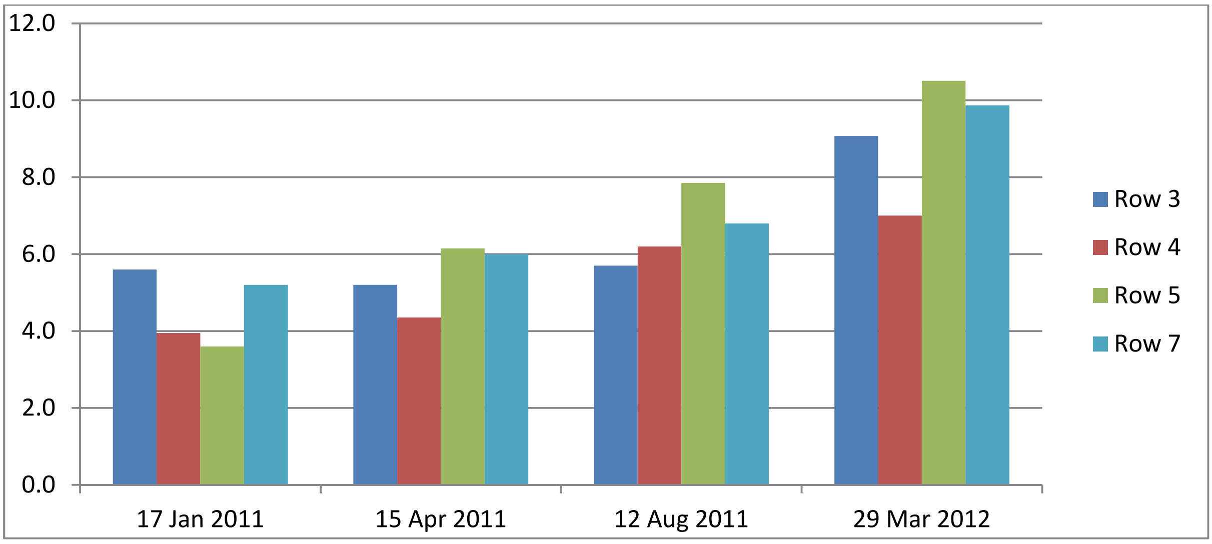


Figure 3.18 Changes in stem diameter at 1.37 m (in cm) for experimental wattle rows over time (mean values)

Table 3.4 Mean values for stem diameters and relative gains in growth for different treatments for wattle trees

	Diameter at 1.37 m			Percentage greater diameter	
Month	**Row 3: sludge**	**Row 5: control**	**Row 7: fertiliser**	**Row 3 over Row 5**	**Row 3 over Row 7**
January 2011	56 mm	36 mm	52 mm	56%	8%
				Row 5 over Row 3	**Row 7 over Row 3**
April 2011	52 mm	62 mm	60 mm	18%	15%
August 2011	57 mm	79 mm	68 mm	38%	19%
March 2012	91 mm	105 mm	99 mm	16%	10%

3.4.3 Groundwater impact

The surface topography of two transects was surveyed on 29 June 2011 in order to determine the water table gradients. The first transect ran from the trench site to the stream and the second along the borehole line from BH2 to BH5 (Figure 3.19). The water table lay at a depth of approximately 2m below the entrenchment site and was typically 5m below surface at the boreholes between the site and the river. The flow from along the hill slope was channelled downward towards the river. Modelling indicated that there would be a 5 mg/ℓ increase in groundwater nitrate levels in the first year after sludge burial, but this was not borne out by observations from the boreholes (Figure 3.20), which showed a lower response. [3]

Figure 3.19 Layout of surveyed transects from trench zone to stream and along the borehole line

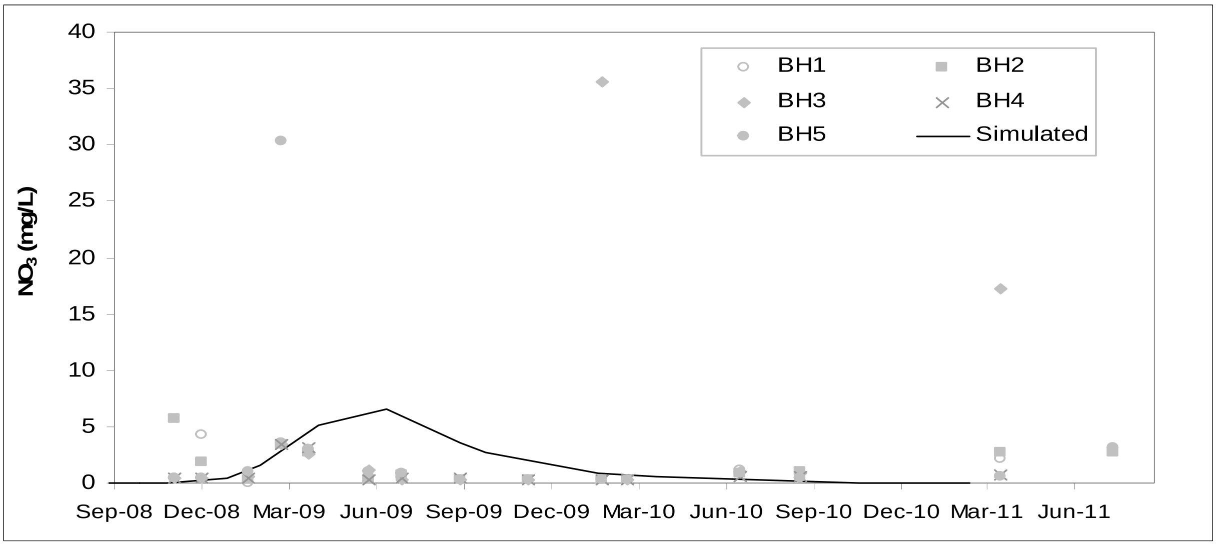


Figure 3.20 Observed (all boreholes) and simulated (node 3) nitrate concentration

[3] There was some difficulty experienced with vandalism of the monitoring boreholes. The two higher outlier readings in Figure 3.20 were associated with these disturbances and were not general. See Appendix D for a record of the results from the monitoring boreholes at the Umlazi site.

Similar observations can be made for the phosphorus plume, shown in Figure 3.21. Due to the strong adsorption of P to the soils, concentrations of the dissolved phase continue throughout the simulation period. The observed concentrations at 0.1 to 0.5 mg/ℓ were higher than those predicted by the simulation (below 0.1), but were nevertheless well below the level at which concern might be warranted (by way of comparison the allowable limit for ortho-phosphate levels in effluent from wastewater treatment works in South Africa is 10 mg/l).

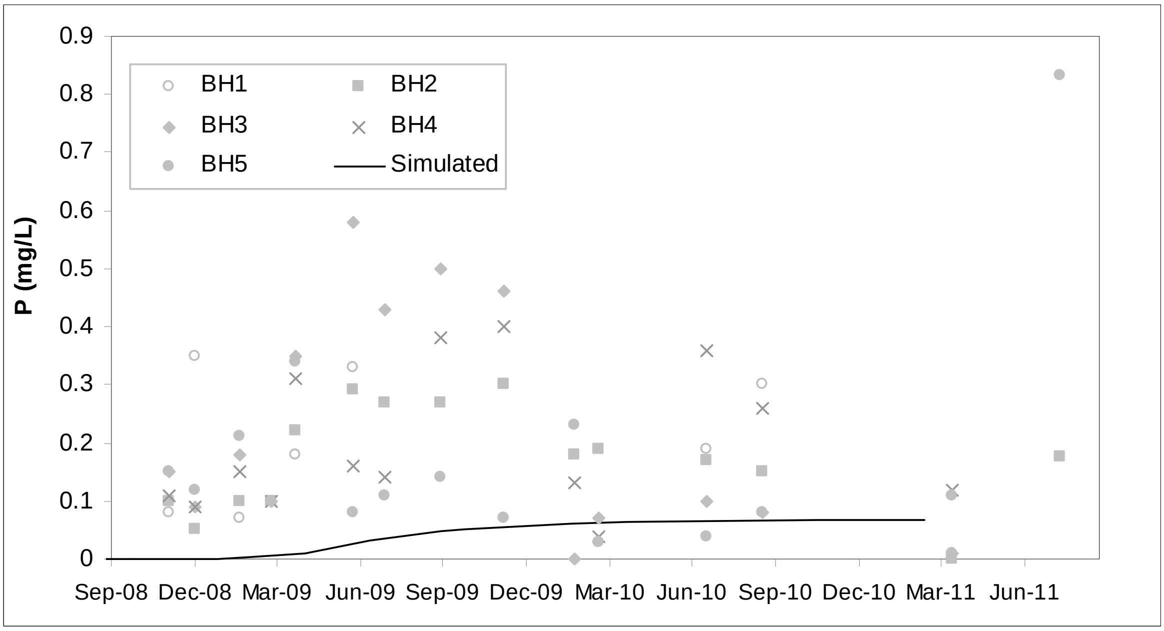


Figure 3.21 Observed (all boreholes) and simulated phosphorus concentration

Tree growth monitoring was discontinued at the Umlazi site in January 2012 due to problems with vandalism and theft of trees.

3.4.4 Sludge Characterisation

Changes in the characteristics of the sludge (COD, Volatile solids, Moisture content) over the duration of the trial have been monitored and these results are included in Appendix E.

Whereas in earlier testing a soil auger had been used to sample the sludge, the sludge was by January 2013 so decomposed that sometimes field workers found it difficult to know whether they had really found the sludge or not. For this reason open pits were dug to reach the sludge layers. All pits were photographed (Figure 3.22).

The COD of the pit sludge at the time of burial (i.e. soon after it had been removed from the pit) ranged from 0.1 g to 0.54 g COD / g dry sample, with a median of 0.25 g. The wide range of values is attributable to the heterogeneous nature of VIP sludge, including fresh both faecal material and older faecal material which would have been in the pit for several years. With the progression of time, as the fresher sludge decomposes, the median value appears to stabilize around 0.11 g COD. After a further eighteen months the COD of 29 samples was found to vary from 0.006 to 0.263 g COD/g dry sample. The median value was then 0.047 g.

The volatile solids content of the pit sludge (i.e. the organic portion, as opposed to grit etc.) at the time of burial (i.e. soon after it had been removed from the pit) ranged from 20 to 85% of the dry sample mass, with a median of 60%. By 30 months the median volatile solids was 25%, although the range (from 0 to 50%) was still wide. After a further 18 months the median volatile solids had decreased to 1.9%, with an average of 3.7%.

Figure 3.22 Four years after burial the sludge is hard to distinguish from the surrounding soil (the plastic is a good clue)

The moisture content of the pit sludge at the time of burial (i.e. soon after it had been removed from the pit) ranged from 60 to 90% g moisture/g wet sample, with a median of 75%. After 30 months the median value was approximately 35%. After a further 18 months the median moisture content has decreased to 13%.

3.5 Burial of activated sludge at Shafton, Natal Midlands

The Howick Wastewater Treatment Works (WWTW) currently disposes of approximately 700 tons of sludge (measured in dry weight) every year at the Curry's Post landfill site. The capacity of the WWTW to dry the sludge to the 40-60% moisture content required for landfill acceptance is limited, particularly during the wet season. In addition, this option fails to exploit the nutrients or energy contained in sludge.

3.5.1 Description of site

In February 2009, Sappi Forests, a forestry/timber plantation company, was asked to participate in a sludge entrenchment trial by providing a site for the experimental burial of sewage sludge from the Howick WWTW. After long negotiations a protocol was approved for burial of sludge at SAPPI's Shafton Karkloof plantation, which is located 10 km east of Howick on the Karkloof road (Figure 3.23). A formal letter from DWAF/WRC stating that they supported the trial was provided before the trial commenced.

The experimental site, which encompasses 2 hectares on gently (11%) sloping ground, was covered with large amounts of timber trash and in line with Sappi's standard practice it was necessary to first burn this before work could begin. In November 2009 the site was pegged out into 30 blocks each 20 m x 20 m in size, with a 10 m buffer zone between blocks (Figure 3.25). Six trenches oriented downslope and spaced 3m apart centre to centre were dug in each block using a TLB (tractor-loader-backhoe) initially and then later using an excavator. Each trench was prepared to dimensions of 20 m in length, 0.6 m width and 1.5 m depth.

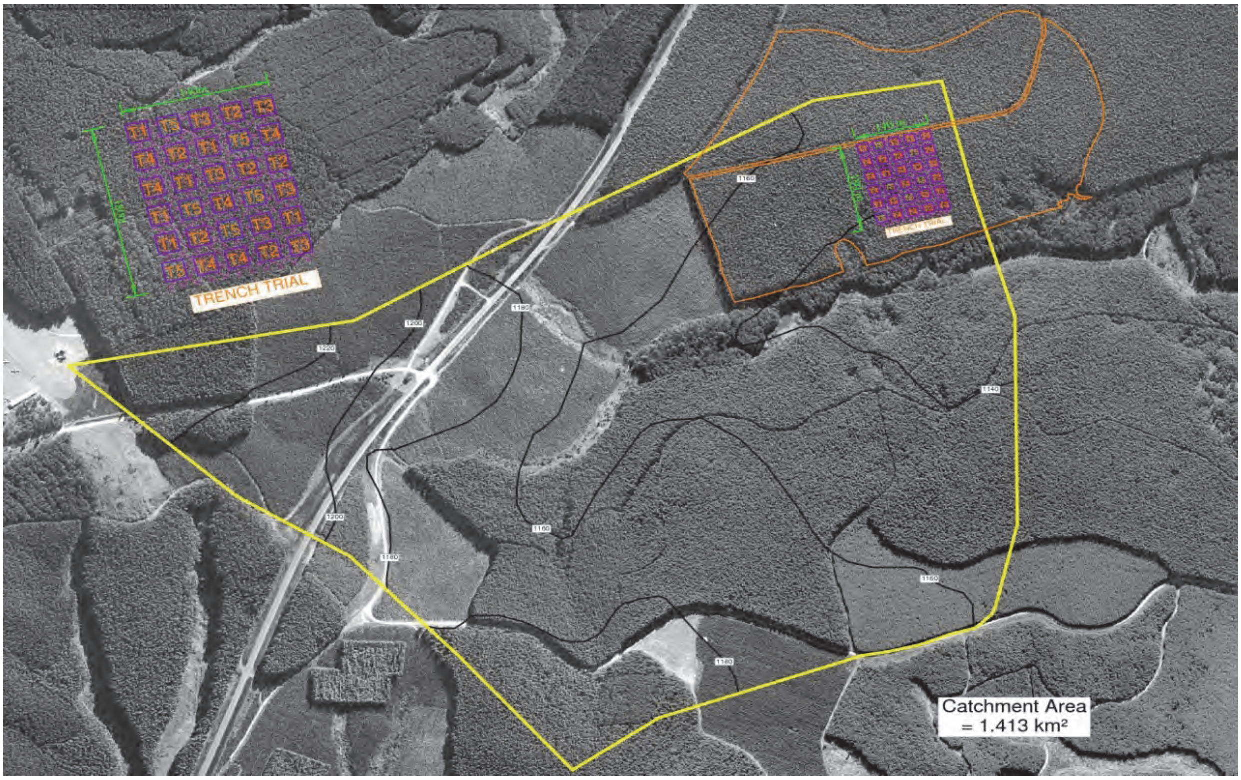


Figure 3.23 Locality of the Sappi site, some 11 km from Howick to the south of the Karkloof Road

Figure 3.24 Commencement of sludge entrenchment at the Sappi site, November 2009

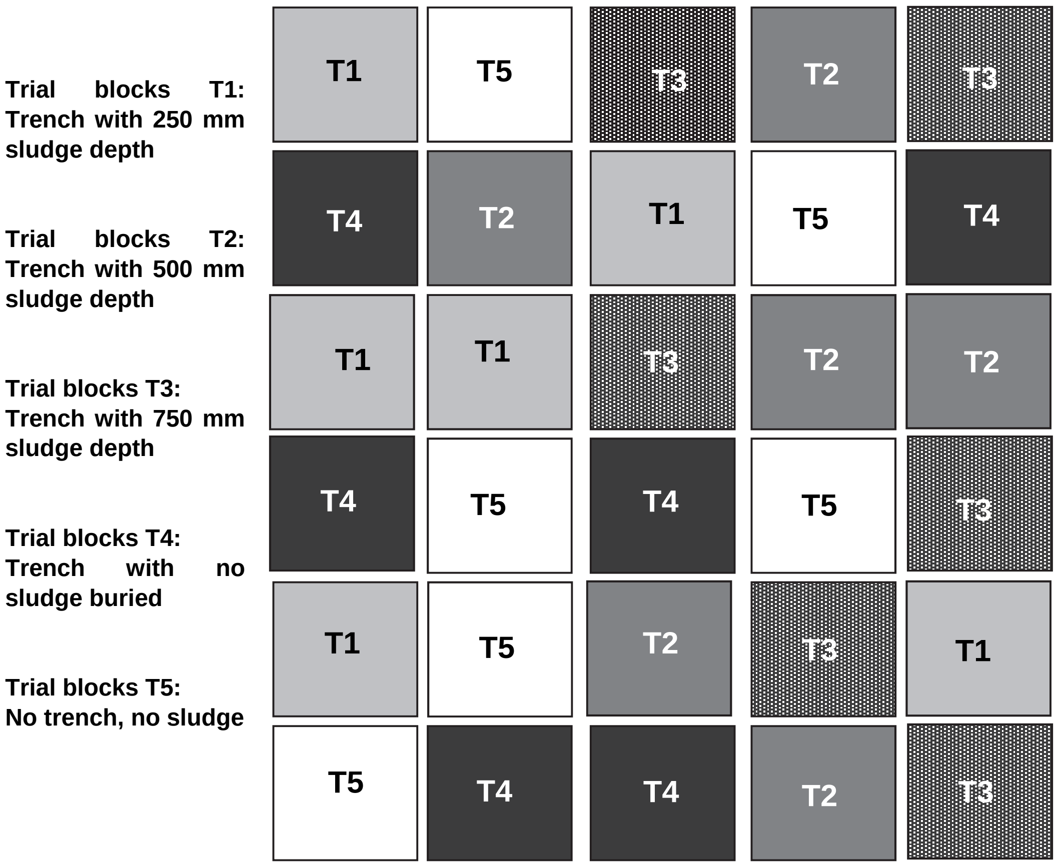


Figure 3.25 Layout of treatment blocks at Sappi site

An excavator was required to dig the trenches in ten of the plots because of large stumps. This also provided tracks into the site for the vehicles transporting sludge. Once the trenches were dug, sludge was carted to the site using tip trucks and the required number of loads was dumped next to each block (Figure 3.26).

Figure 3.26 Prepared trench (left) and delivery of sludge from WWTW (right)

3.5.2 Sludge application

The sludge entrenched at Shafton would be classified as C1a (i.e. untreated for pathogens, stable, low pollutant content). Sludge samples were also analysed for water holding capacity, hydraulic conductivity and nutrient content. Moisture levels were found to be higher (60%) and nitrogen levels lower (1.88%) than expected. The latter is probably because the sludge had been stockpiled for up to 6 months prior to the commencement of the study, which would have allowed a portion of the nitrogen content to either leach away or volatilize. The entrenchment took place during a period of wet weather, which would have increased the moisture content.

Five different treatments were allocated randomly to the 30 blocks (Figure 3.25. The trenches were backfilled to allow the required amount of sludge to be filled to 300 mm below the surface. Thereafter each treatment was topped with 300 mm of the excavated topsoil. The five treatments comprised:

- Treatment 1 (T1): 250 mm sludge (120 dry tons/ha), providing 2 250 kg nitrogen/hectare
- Treatment 2 (T2): 500 mm sludge (240 dry tons/ha), providing 4 500 kg nitrogen/hectare
- Treatment 3 (T3): 750 mm sludge (360 dry tons/ha), providing 6 750 kg nitrogen/hectare
- Treatment 4 (T4): Control: trench dug and refilled with no sludge application
- Treatment 5 (T5): Control: No trench, no sludge. Standard planting in small holes.

These application rates were achieved by applying one 10 ton load of sludge on every T1 block, two loads on every T2 block and three loads on every T3 block. The total amount of sludge applied over the 150 metre by 180 metre research site (an area of 2.7 hectares) was therefore 360 wet tons or approximately 280 m^3. The dry tonnage applied over the whole research site was 144 tons. With a nitrogen content of 1.88% this equates to 2 707 kg of nitrogen applied in total over the 2.7 hectares.

Trees were planted evenly across the entire site in January 2010. This means that they had been growing for 52 months by May 2014, when the most recent growth measurements were taken.

With the trees soon being too tall for easy measurement of their height, comparison of growth is made by measurement of the diameter at chest level (1.37 m), which is the convention in the forestry industry. There is a linear correlation between tree height and this diameter (Figure 3.27), so the *relative* volume of timber in different stands can be assessed by comparing their diameter^3 s.

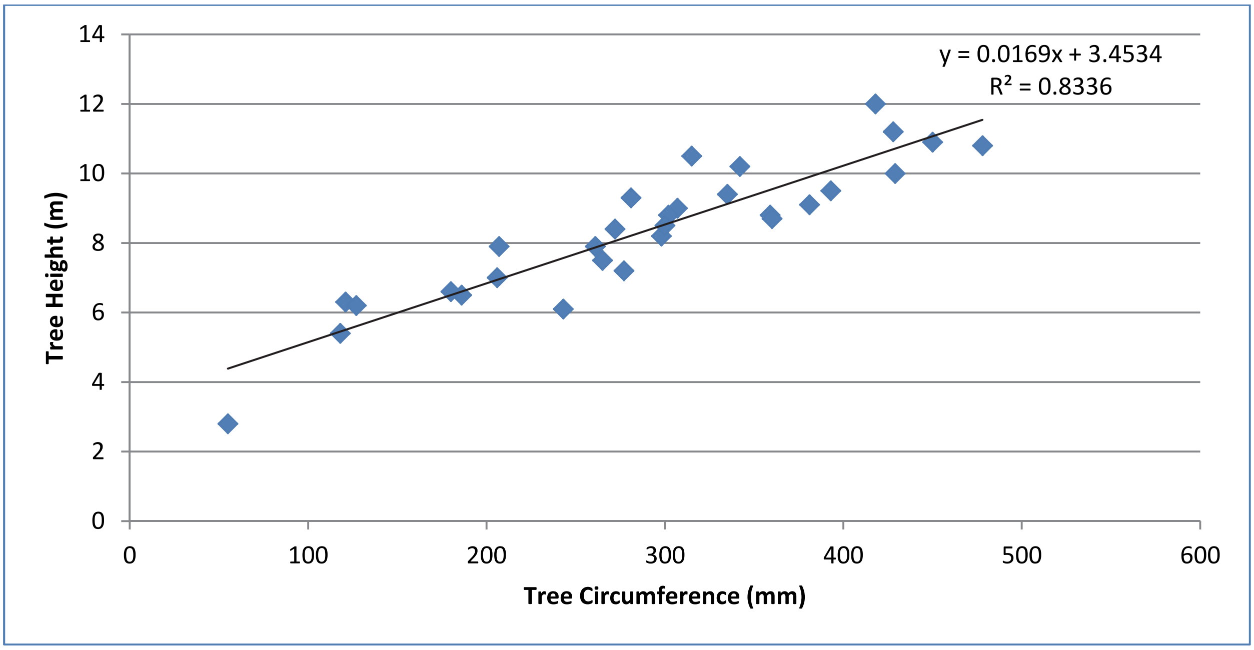


Figure 3.27 Correlation between tree height and diameter measured at Sappi site

Tree growth data is corrected for mortalities. In each plot a central section was measured to make up 30 trees in total[4] (Figure 3.28). If one of the trees had died this was counted with a zero diameter and included in the statistics, in order to get a true comparison between the plots. The comparative mortality of the different plots is shown over time in Figure 3.29. While the mortality of the T5 plots is higher, there is an increasing mortality trend in the T1 and T3 blocks. The reason for the anomalous decrease in mortality between 28 April 2011 and 17 November 2011 is that Sappi do routinely look for early mortalities and then replant. On the evidence of Figure 3.29 is does appear that the digging of the trenches has reduced tree mortality, whether sludge is applied or not. This is probably a positive effect of loosening the soil for easier root growth.

[4] For the first two sets of readings 8 tree by 4 rows, i.e. 32 trees, were measured in the centre of each plot. This was later changed to 6 trees by 5 rows, i.e. 30 trees, to better represent the middle portion of the plot.

20m (width); 20m (spacing between plots)

	1	2	3	4	5	6	7
1	+	+	+	+	+	+	+
2	+	1	16	17	32	+	+
3	+	2	15	18	31	+	+
4	+	3	14	19	30	+	+
5	+	4	13	20	29	+	+
6	+	5	12	21	28	+	+
7	+	6	11	22	27	+	+
8	+	7	10	23	26	+	+
9	+	8	9	24	25	+	+
10	+	+	+	+	+	+	+

20m (width)

	1	2	3	4	5	6	7
1	+	+	+	+	+	+	+
2	+	+	+	+	+	+	+
3	+	1	12	13	24	25	+
4	+	2	11	14	23	26	+
5	+	3	10	15	22	27	+
6	+	4	9	16	21	28	+
7	+	5	8	17	20	29	+
8	+	6	7	18	19	30	+
9	+	+	+	+	+	+	+
10	+	+	+	+	+	+	+

(light grey)	8 * 8 Grid	Measured from 4 Nov 2010 until 17 Nov 2011
(dark grey)	6 * 5 Grid	Changed to 6 * 5 from 21 March 2012

Figure 3.28 Location of trees measured in each plot

A total of 180 trees were measured for each of the five treatments, which (unlike the other trials described above) is a statistically more significant number.

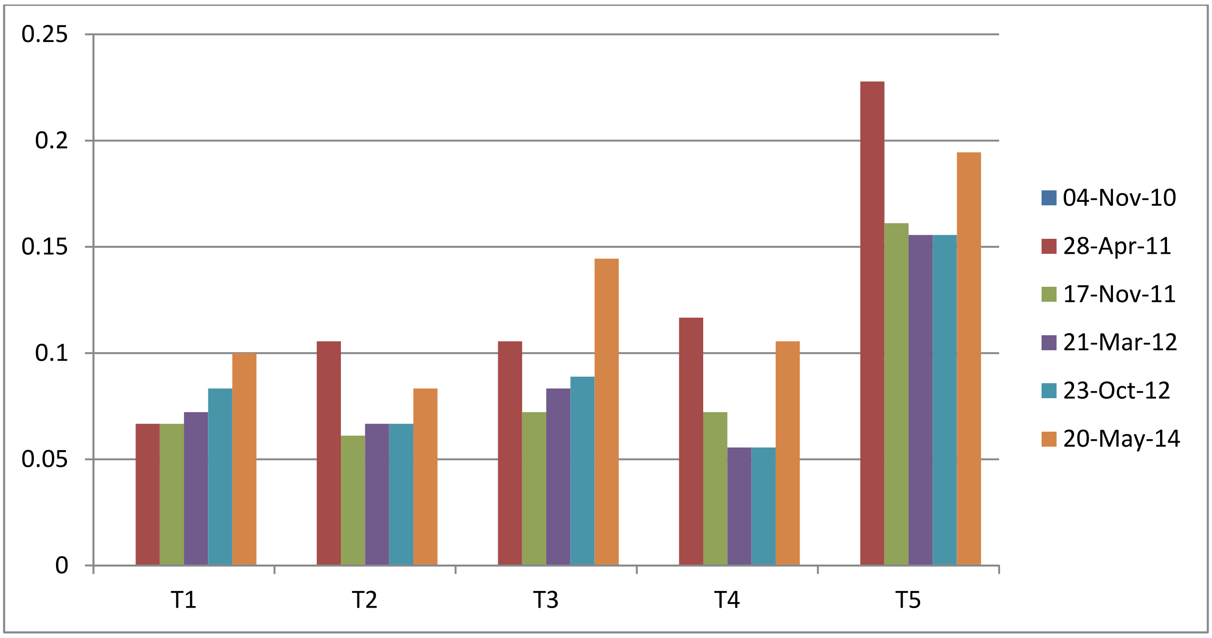


Figure 3.29 Comparative mortality between the five different plots, over time

Table 3.9 shows the comparison of the median equivalent diameters^3 between the five different plots T1 to T5. Diameter^3 is a good basis for estimating the relative difference in timber volume between the different blocks, as tree height has a linear correlation with diameter. Note that during the first year after planting the trees were still too small for the chest height diameter measurement to be meaningful.

Table 3.5 Comparison of the median diameter^3 for the five different blocks (mm^3).
[As per convention in the forestry industry, the diameter measurement is taken at chest height, 1.37 m.]

Median Equivant Diameter^3 (including dead) (mm)								
	28-Apr-11	**17-Nov-11**	**21-Mar-12**	**23-Oct-12**	**30-Apr-13**	**15-Oct-13**	**20-May-14**	
T1	183 579	596 052	1 284 075	2 024 975	2 508 876	3 025 909	3 535 564	*250mm Sludge*
T2	225 739	557 503	1 303 465	1 950 935	2 335 684	2 688 006	3 223 988	*500mm Sludge*
T3	233 251	511 606	1 264 836	1 986 860	2 329 095	2 714 268	3 171 295	*750mm Sludge*
T4	79 813	292 220	689 971	1 058 285	1 476 023	1 846 829	2 385 749	*Trench, No Sludge*
T5	110 588	369 872	883 861	1 328 630	1 619 402	1 981 842	2 410 675	*No Trench, No Sludge*

The data in Table 3.9 is shown graphically in Figure 3.30. The trees growing on the blocks treated with sludge do show a clear advantage, although it is notable that there is no benefit gained by increasing the amount of sludge beyond the level which can be beneficially used. In fact with the T2 and T3 growth dropping away from the T1 growth, if anything the converse is true.

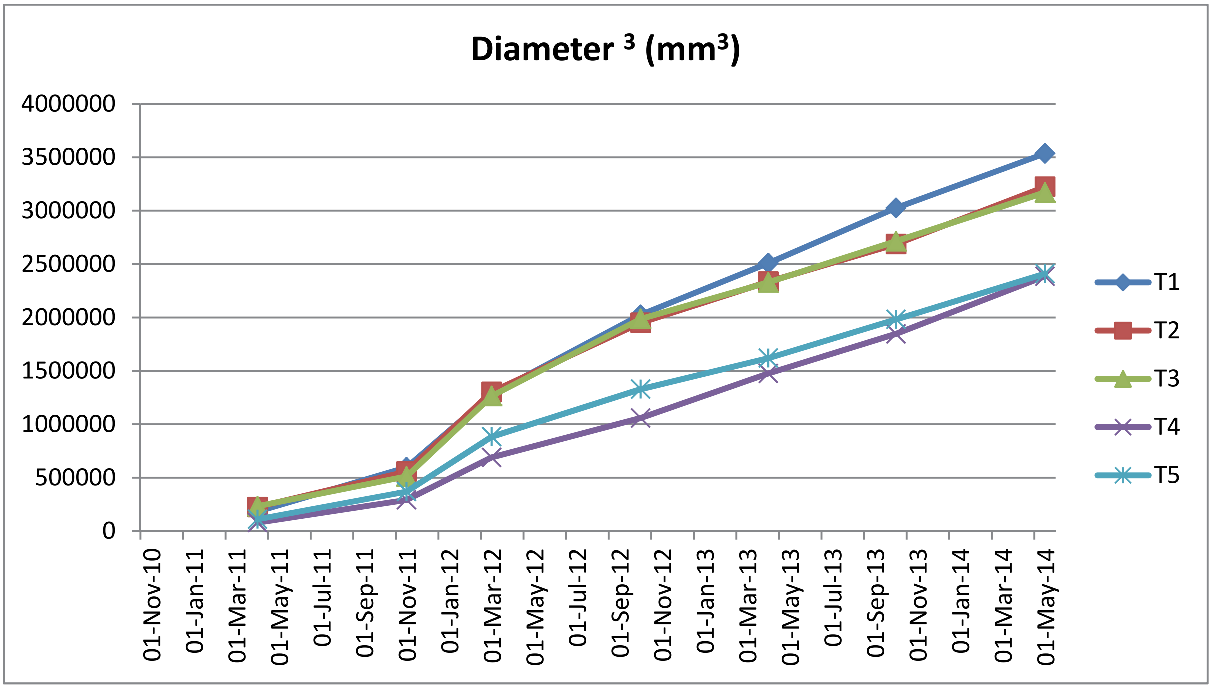


Figure 3.30 Comparison of the median diameter^3 for the five different treatment types.

In order to assess what difference the sludge has made to the tree growth, a more helpful comparison is the *percentage* difference between T1, T2, T3 and T4 measured relative to T5. This comparison is shown in Figure3.31 below

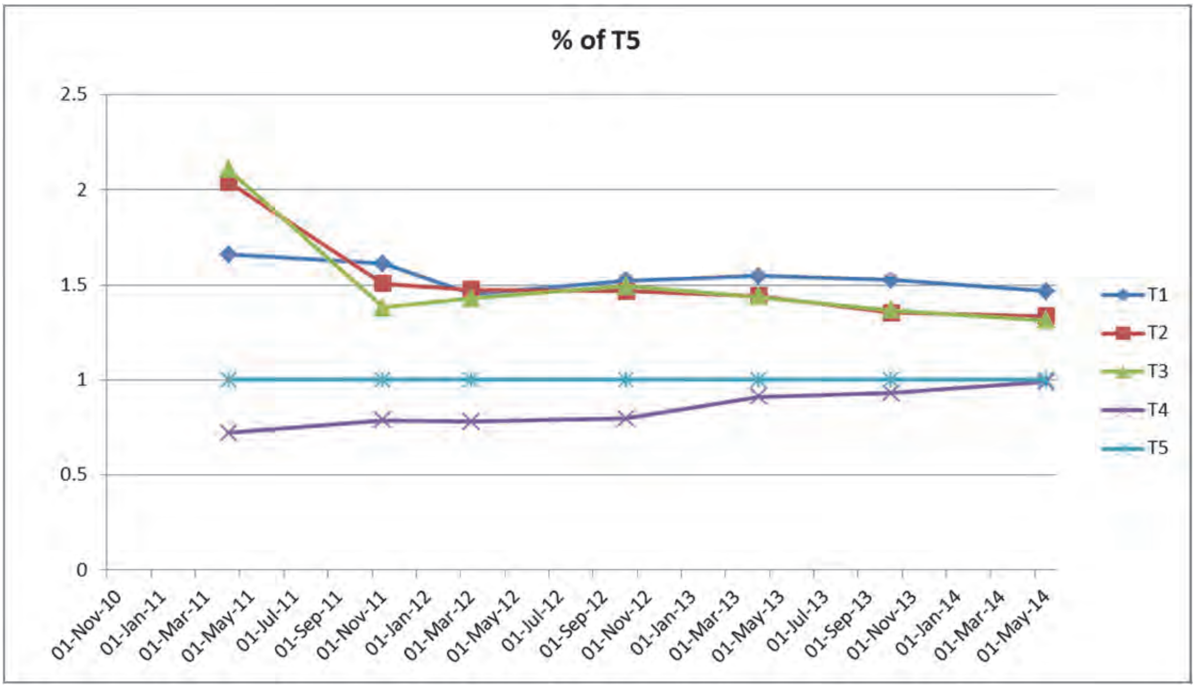


Figure 3.31 Comparison of *relative* difference in tree growth (measured as diameter^3)

The trends shown in Figure 3.31 show that after four years T4 has caught up with T5. Neither of these treatments had any sludge. Of the three treatments which did have sludge, there was a more marked early response from the treatments with extra sludge (T2 and T3), but this was not sustained, and latterly these two treatments have been falling away from T1 which is now consistently ahead.

The trees were planted in mid-January 2010. After 52 months' growth the indicated timber volume on the T1 plots is 50% greater than that on the untreated T5 plots. While this relative difference has been fairly consistently maintained over the last two years, a projection of the trends apparent in Figure 3.31 does suggest that the final difference after a full growth cycle (9 to 10 years) may be less than 50%.

3.5.3 Groundwater impact

The impact of the sludge on the local groundwater was measured using a variety of instruments, more fully described in the final WRC report on Project K5/1829 – "Investigating the potential of entrenchment of pit latrine and wastewater treatment works sludge for forestry and land rehabilitation purposes". A number of piezometers, wetting front detectors and other groundwater monitoring instruments were distributed as shown in Figure 3.32. The measurements of most interest were those in the two boreholes which were drilled for monitoring purposes below the site, as well as the two piezometers (SP6 and SP7) located on drainage lines below the site.

Figure 3.32 Location of groundwater monitoring instrumentation, Sappi site

Figure 3.33 shows the nitrate concentrations measured in the boreholes and the stream over the period May 2010 to August 2011. The nitrate levels of both boreholes and the stream do show an increase over the period, particularly over the rain season. However, the increase in the nitrate levels in Borehole 1, which is well above the site and therefore unlikely to be affected by the experiment, is as marked as the increase in Borehole 2, which is below the site. There is also a seasonal increase in the nitrate levels in the stream. The nitrate levels in Borehole 2 were generally approximately 3 mg/ ℓ higher than the levels in Borehole 1. This difference may be due to the entrenchment of the sludge.

Nitrate concentrations in piezometers SP6 and SP7 varied widely: concentrations in piezometer SP6 ranged from 10 to 200 mg/ℓ while concentrations in the piezometer SP7 ranged from 100 to 700 mg/ℓ (see Figure 3:34). These variations reflected accumulation along preferential flow paths during the wet season rather than a direct response to rainfall events. SP6, located in a subsurface waterway, had a deeper flow regime than that of SP7 and also continued for much longer than SP7. Concentrations in SP6 were similar to those intercepted by the wetting front detectors in the trench profiles, suggesting a connection between the infiltrated water and the accumulated subsurface, free water discharge at the soil/bedrock interface. This mechanism of the interception of buried waste by rapid, near surface lateral flow is often overlooked and requires monitoring and assessment of the total load from these pathways.

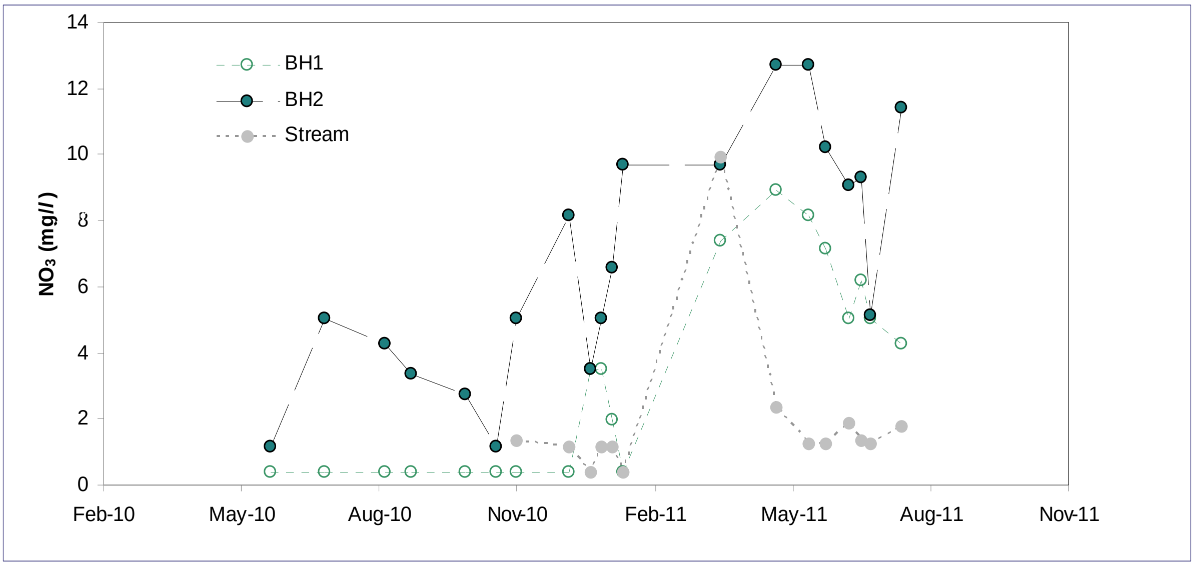


Figure 3.33 Observed nitrate concentration in boreholes and stream

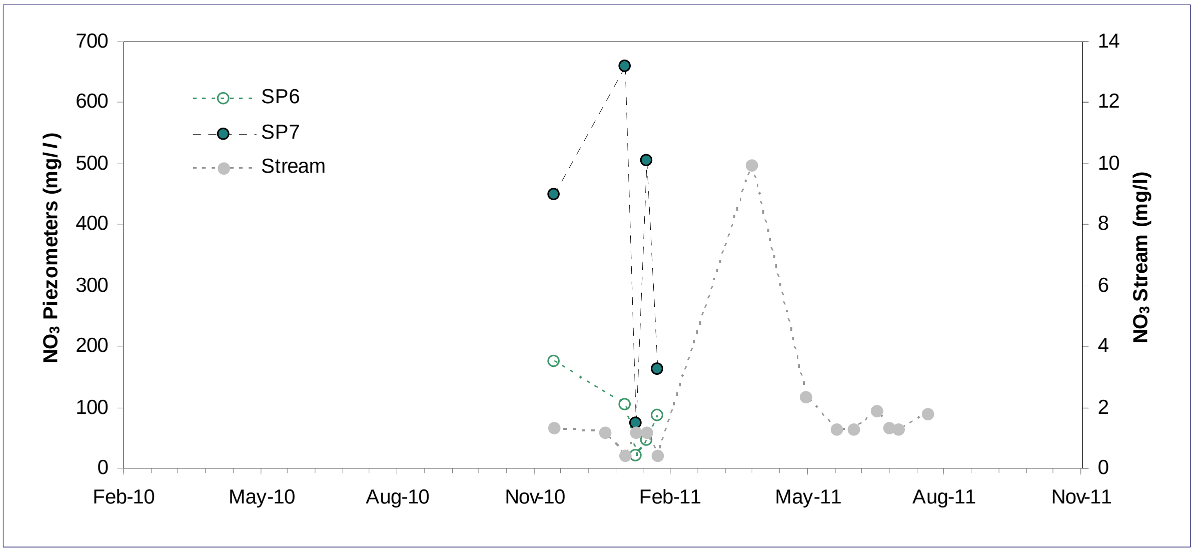


Figure 3.34 Observed nitrate concentration in piezometers (SP6 and SP7) and stream

While the nitrate concentrations in SP6 and SP7 were at times high, there was no way of measuring the flow along these pathways and therefore it was not possible to say what mass of nitrogen was transferred by the near surface flow intercepted by these piezometers. The other piezometers located higher up the slope were generally found to be dry and therefore did not contribute data.

Phosphorus (P) concentrations in the boreholes and stream varied throughout the monitoring period, but appeared to increase from May 2011 onwards (Figure 3.35). The range of P concentrations in the boreholes was equal to that in the stream and was assumed to be similar to subsurface contributions upstream of the trial site.

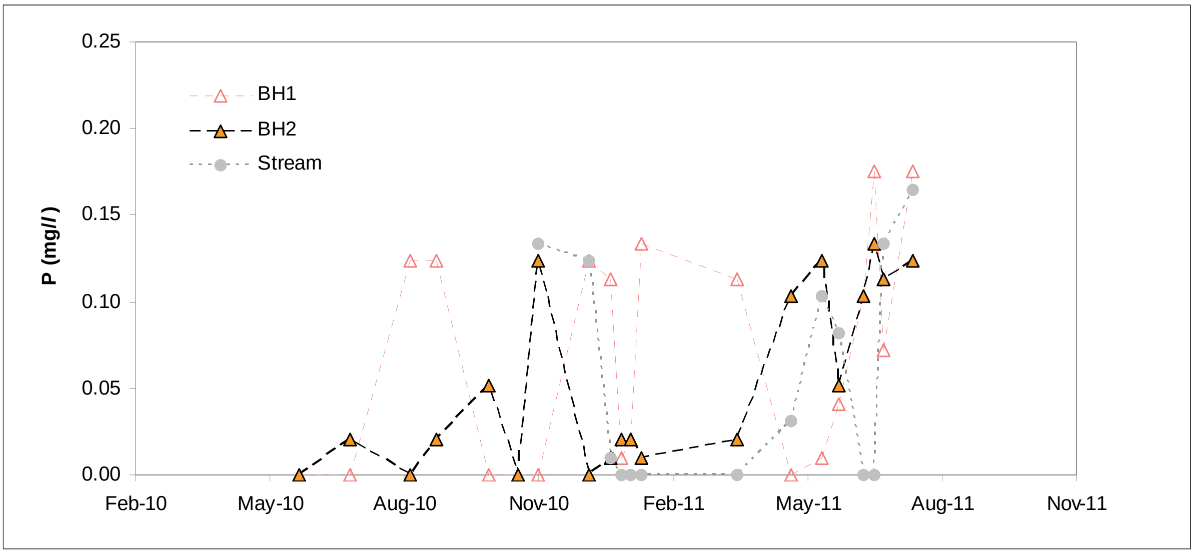


Figure 3.35 Observed phosphorus concentrations in boreholes and stream

Phosphorus concentrations ranged widely (0.1-23 mg/ℓ) in the piezometers SP6 and SP7, with SP6 having higher phosphorus concentrations than SP7.

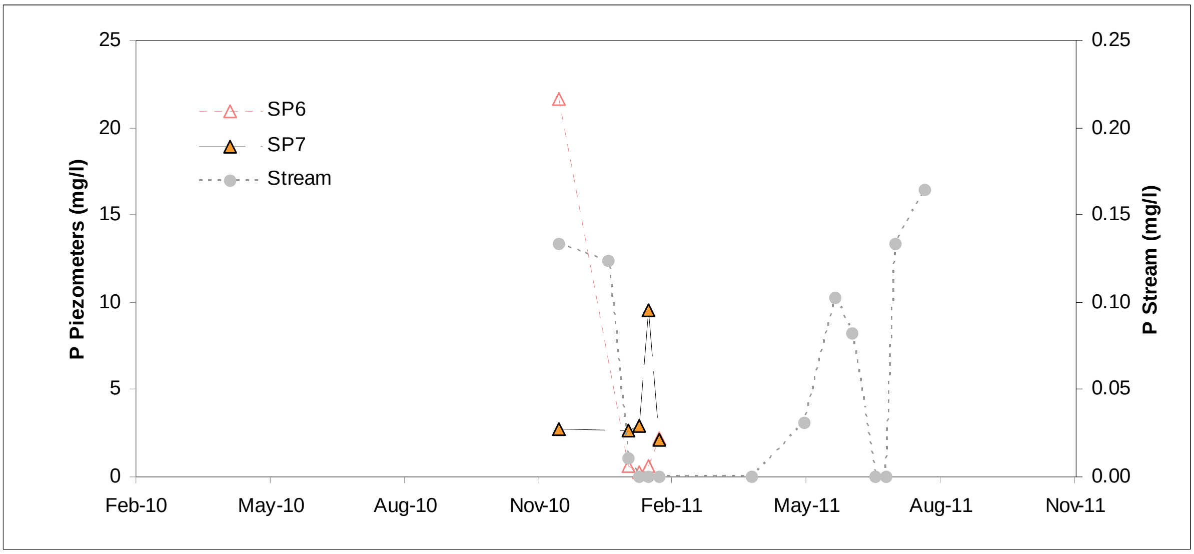


Figure 3.36 Observed phosphorus concentrations in piezometers and stream

Measurements of nitrate and phosphorus in the groundwater at the Sappi site were made again in October 2013 and January 2014 (Table 3.6). For comparison the nitrate and phosphorus content of the water in the raingauge on the site was also analysed. The samples were taken after periods of heavy rainfall. Although just two sets of readings is not enough for a very detailed analysis, the following observations can be made:

The nitrate levels in the boreholes, piezometers and stream were all significantly lower than those observed during the previous observation period (which was the wet season of 2010/2011). Apart from the wetting front detectors which are taking samples from within or very close to the sludge, the highest nitrate reading was observed in the rainwater in the January sample (6.38 mg/ℓ, which was four to six times the concentration observed in the boreholes and stream at the same time).

The phosphorus levels observed were not very different to those found during the previous monitoring period. The phosphorus concentration found in the rainwater sample on 20 January 2014 was higher than the concentration found in any of the groundwater samples on that day.

Table 3.6 Phosphorus and Nitrate measurements at SAPPI site, 2013/14 rain season

		Phosphorus concentration (mg/l)		Nitrate concentration (mg/l)	
TYPE	Sample ID	30-Oct-13	20-Jan-14	30-Oct-13	20-Jan-14
BOREHOLES AND STREAMS	BH1	0.24	0.15	0.66	0.8
	BH2	0.33	0.13	0.09	0.92
	STREAM BELOW BH1	0.16	0.11	1.73	0.84
	STREAM BELOW BH2	0.16	0.11	2.26	1.7
PIEZOMETERS (those not shown, i.e. SP1, 3, 4, 5 and 7) were dry at the times of sampling	SP2	-	0.09	-	0.58
	SP6	-	0.05	-	0.82
WETTING FRONT DETECTORS Treatment (depth at which measured)	T1 (0.4 m)	-	0.37	-	56.7
	T1 (1.0 m)	0.17	0.31	79.2	66.3
	T2 (0.4 m)	0.67	0.1	35.48	33.6
	T2 (1.0 m)	-	-	-	-
	T3 (1.0 m)	0.44	0.21	38.6	31.2
	T4 (0.4 m)	0.21	0.43	0.29	3.6
	T4 (1.0 m)	0.26	0.21	3.32	11.2
RAIN-SAPPI	FROM RAINGUAGE	0.19	0.54	0.1	6.38

Residual Nitrogen and Phosphorus in sludge and the surrounding soil

The results of the groundwater monitoring suggest that the entrenchment of 360 m^3 of sludge (144 dry tons) over the 2.7 hectare research site has not made a significant impact on the local groundwater. In order to gain a better understanding of the fate of the nutrients and other elements in the buried sludge, in February 2013 a number of soil samples were taken from within and in close proximity to the sludge and analysed. Figures 3.37, 3.38 and 3.39 illustrate the locations of the soil samples, and Table 3.7 shows the results from the soil samples taken close to the entrenched sludge (locations A, B and C). Figure 3.40 shows an exposed trench with sludge.

Additional soil samples were taken along transects above and below the test site (D and I).

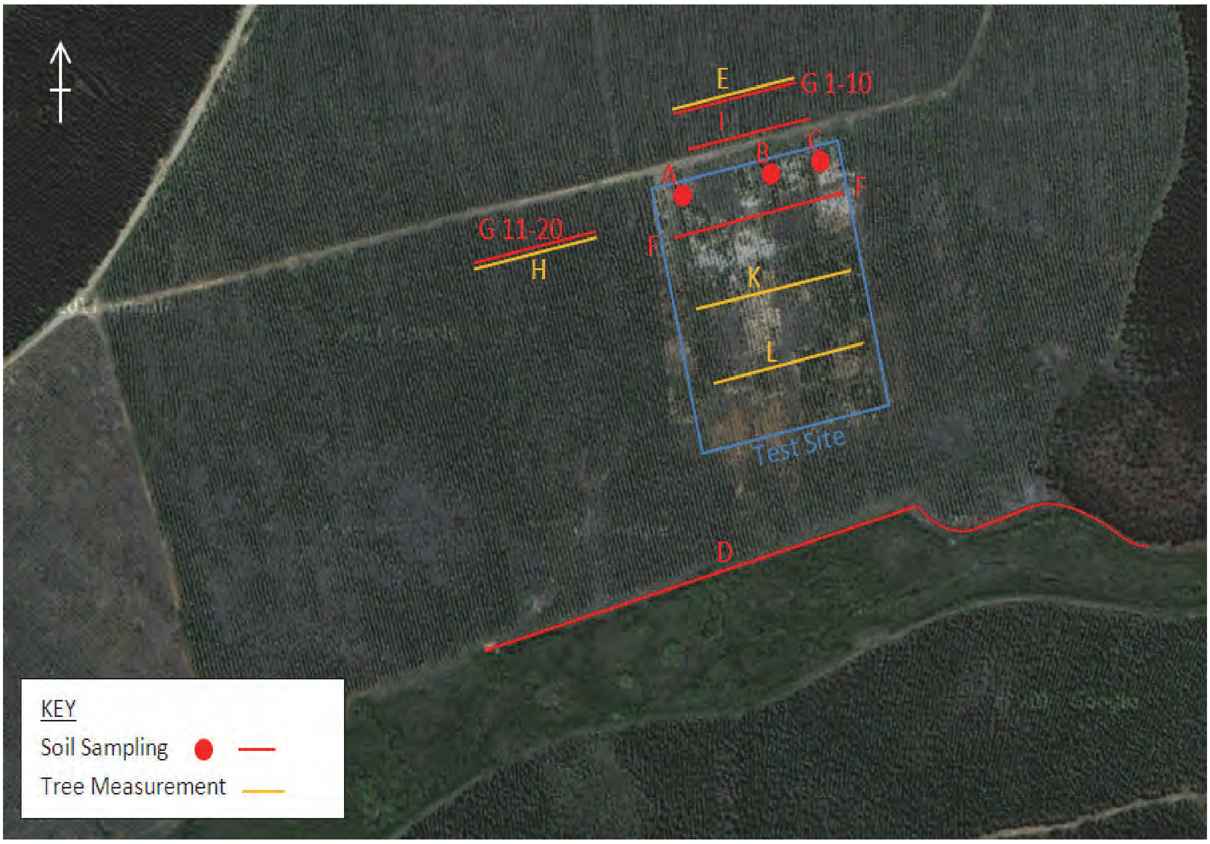


Figure 3.37 Locations of soil samples at Sappi site in February 2013

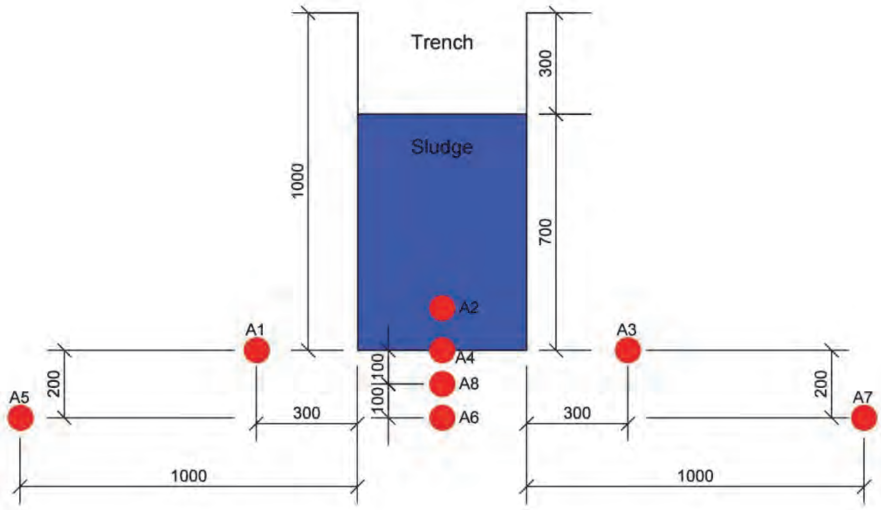


Figure 3.38 Section View showing locations of soil samples around entrenched sludge

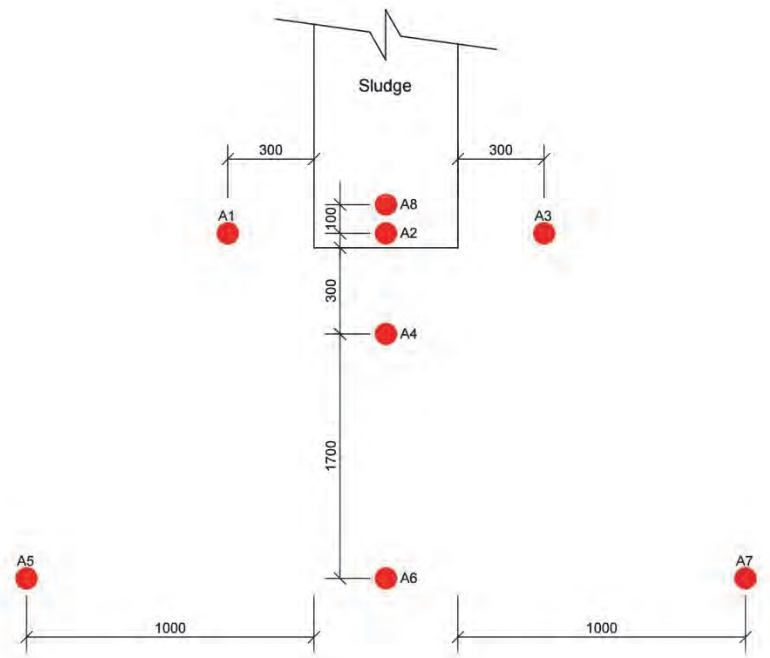


Figure 3.39 Plan View showing locations of soil samples around entrenched sludge

Table 3.7 Analysis of sludge and soil samples taken from Sappi sludge entrenchment site

Sample ID	Sample density g/mL	P mg/kg dry	K mg/kg dry	Ca mg/kg dry	Mg mg/kg dry	pH (KCL)	Zn mg/kg dry	Mn mg/kg dry	Cu mg/kg dry	Org.C %	N %
A1	0.85	1.2	20.0	27.1	47.1	3.99	0.2	1.2	0.6	1.2	0.14
A2	0.76	11.8	31.6	59.2	51.3	3.82	1.1	2.6	2.5	6	0.45
A3	0.83	7.2	36.1	36.1	31.3	3.94	0.6	1.2	1.1	1.7	0.14
A4	0.85	5.9	35.3	20.0	20.0	3.98	0.5	1.2	0.9	1.5	0.15
A5	0.85	2.4	23.5	15.3	18.8	3.97	0.4	1.2	0.6	0.9	0.16
A6	0.88	1.1	22.7	23.9	28.4	3.92	0.1	1.1	0.7	1.1	0.14
A7	0.86	1.2	15.1	37.2	17.4	3.98	0.2	1.2	0.6	1.6	0.15
A8	0.86	3.5	25.6	93.0	59.3	4	0.2	1.2	0.6	0.8	0.15
B1	0.72	20.8	63.9	329.2	43.1	3.86	0.7	4.2	3.1	6	0.52
B2	0.8	300.0	107.5	947.5	176.3	3.72	62.6	23.8	20.1	5.4	0.43
B3	0.75	20.0	130.7	96.0	21.3	3.78	0.4	4.0	3.3	6	0.44
B4	0.9	4.4	30.0	90.0	60.0	3.97	0.8	7.8	1.0	2.1	0.33
B5	0.86	2.3	24.4	32.6	57.0	4.13	0.3	1.2	1.0	2.6	0.19
B6	0.86	8.1	54.7	122.1	59.3	3.94	0.3	5.8	1.9	3.8	0.32
B7	0.89	4.5	34.8	30.3	93.3	3.97	0.2	2.2	1.7	3.7	0.31
B8	0.94	14.9	85.1	256.4	101.1	4.11	3.2	12.8	1.3	1.6	0.52
C1	0.85	51.8	42.4	96.5	84.7	3.89	5.1	3.5	4.0	2	0.23
C2	0.87	344.8	74.7	731.0	273.6	3.8	46.2	16.1	18.6	4.6	0.42
C3	0.91	5.5	35.2	0.0	47.3	4.15	0.4	1.1	0.7	1.4	0.32
C10	0.82	29.3	62.2	125.6	90.2	3.97	3.0	4.9	4.5	4.1	0.31
C11	0.85	8.2	50.6	38.8	49.4	4.01	0.7	1.2	1.8	1.7	0.32
C12	0.81	12.3	63.0	103.7	40.7	3.85	1.0	3.7	3.8	3.2	0.28
Background levels:											
I1	0.93	5.4	45.2	131.2	44.1	3.98	0.9	3.2	1.3	3.4	0.23
I2	0.81	3.7	32.1	30.9	2.5	3.99	0.1	1.2	1.5	2.7	0.25
I3	0.84	10.7	91.7	36.9	17.9	3.96	0.5	1.2	2.1	4.7	0.33
I4	0.83	7.2	50.6	78.3	16.9	3.93	0.4	2.4	1.9	4.2	0.32
I5	0.87	5.7	41.4	31.0	40.2	3.97	0.5	2.3	0.8	2.2	0.32

Samples A2, B2 and C2 were taken (or were meant to have been taken) from within the entrenched sludge (see Figure 3.38). However, the appearance of the sludge and the top soil were so similar that the sampling team struggled to identify with certainty what was sludge and what was not. In Table 3.7 above it can be seen that samples B2 and C2 are quite distinctive (particularly in terms of Calcium, Magnesium and Zinc), whereas sample A2 is not clearly different to the surrounding soil samples. As the sludge was derived from a wastewater treatment works it was fairly heterogeneous and therefore it must be concluded that the sampling team in fact missed the sludge when they took sample A2. At site C the sampling team again experienced difficulty ascertaining where the sludge began and ended, and were therefore unable to obtain samples C4 to C9. Samples C10, C11 and C12 were taken downslope of where C5, C6 and C7 would have been (refer to Fig. 3.39). The sampling team reported that it was clear that the sludge entrenchment process was not as clean and precise as was intended, which at times made it hard to determine where to take samples.

Figure 3.40 Appearance of sludge 38 months after entrenchment

The most noticeable differences between the soil samples and the sludge samples are the Phosphorus, Zinc, Calcium and Magnesium levels, which are well above those for the surrounding soil. The Potassium (K) levels are also somewhat elevated.

The impact of the sludge on mineral levels in the surrounding soil is not distinguishable from background levels except for those samples taken in very close proximity to the sludge (for example, elevated phosphorus can be seen in samples B1, B3, B8, C1 and C10, but in no other samples).

As notable as the high retention of P, K, Ca, Mg and Zn in the sludge, is the complete absence of any significant difference between the sludge, the surrounding soil and the background soil as far as the total Nitrogen content is concerned. In other words, three years after entrenchment, all the additional nitrogen that was added with the sludge has disappeared. No significant increase in nitrate in the groundwater was detected, which indicates that any nitrogen which has not been taken up in the trees has been disposed of by denitrification in the soil, passing back into the atmosphere in the gaseous form, N_2. The final experimental work carried out under this project was designed to test this hypothesis.

3.6 Closely controlled leachate monitoring trial

The Umlazi and Sappi sludge entrenchment trials showed no significant impact on the local groundwater. However, it remained possible that nutrients had nevertheless entered the groundwater through a path that remained undetected by the boreholes and piezometers on site. It was therefore decided to conduct one further experiment designed to ensure that no leachate could be missed.

The controlled experiment (which is still in progress) investigating the impact of nutrient migration from a burial of wastewater treatment work (WWTW) sludge in a pit on the surrounding soil and water resources has been conducted as follows[5]:

1. **Site characterization** including soil survey and soil hydraulic properties. The soil survey comprised soil samples up to 120 cm depth on selected positions of the hillslope (upper, middle and lower) in order to select the suitability of the variation in soil type and depth of soils for the deep row sludge applications. The measurement of soil hydraulic characteristics (water retention on core soil samples and *in-situ* hydraulic conductivity) to interpret the observed water and nutrient movement and provide soil water flow parameters for the simulation of water and nutrient fluxes.
2. **Digging of pits** to the required dimensions for the burial of sludge on selected sites (three locations were screened based on the north-south gradient of changing soil texture and slope). The actual disturbance at each of the three locations comprised 5 small pits (four treatments and one control). It also includes installation of pan lysimeters on two of the selected pits per location.
3. **Instrumentation and Sludge Application**. During the application of a weighed mass of sludge to the treatment pits to the appropriate depths, soil-water measuring (Watermark and Time Domain Reflectometry) and sub-surface water sampling equipments (Wetting front detector and Suction cup) were installed to monitor water and nutrient dynamics in the sub-surface. Background sludge samples were collected at the time of application of the sludge to establish baseline conditions.
4. **Leachate monitoring.** Subsequent to sludge applications, subsurface water samples have been collected and soil water values have been observed under natural rainfall conditions. These can be used to quantify the rate and concentration of nutrients in the soil and water resources. This monitoring also includes sample of rainwater to quantify the concentration of nutrient inputs to the soil, and the analysis of the foliar nutrient content of the grass growing over each of the pits to determine the plant nutrient uptake. After the end of the wet season a rainfall simulator has been used to extend the data collection period.

Site location and characteristics

The study area is located on a land at the back of PID's offices at 51 Roberts Road, Pietermaritzburg, South Africa (latitude 29^{0}35'S, longitude 30^{0}21'E, altitude 655 m). The three study sites (Fig.3.41) were selected to investigate the impact of soil and slope variations on the subsurface nutrient fate.

[5] This experiment is being conducted by Goitom Adhanom and Simon Lorentz and is summarized here. When the work is complete it will be published independently.

In general, the study area has three distinctive slope characteristics including the upper, middle and lower hillslope sections. A fence boundary exists between the east and the west directions of the property.

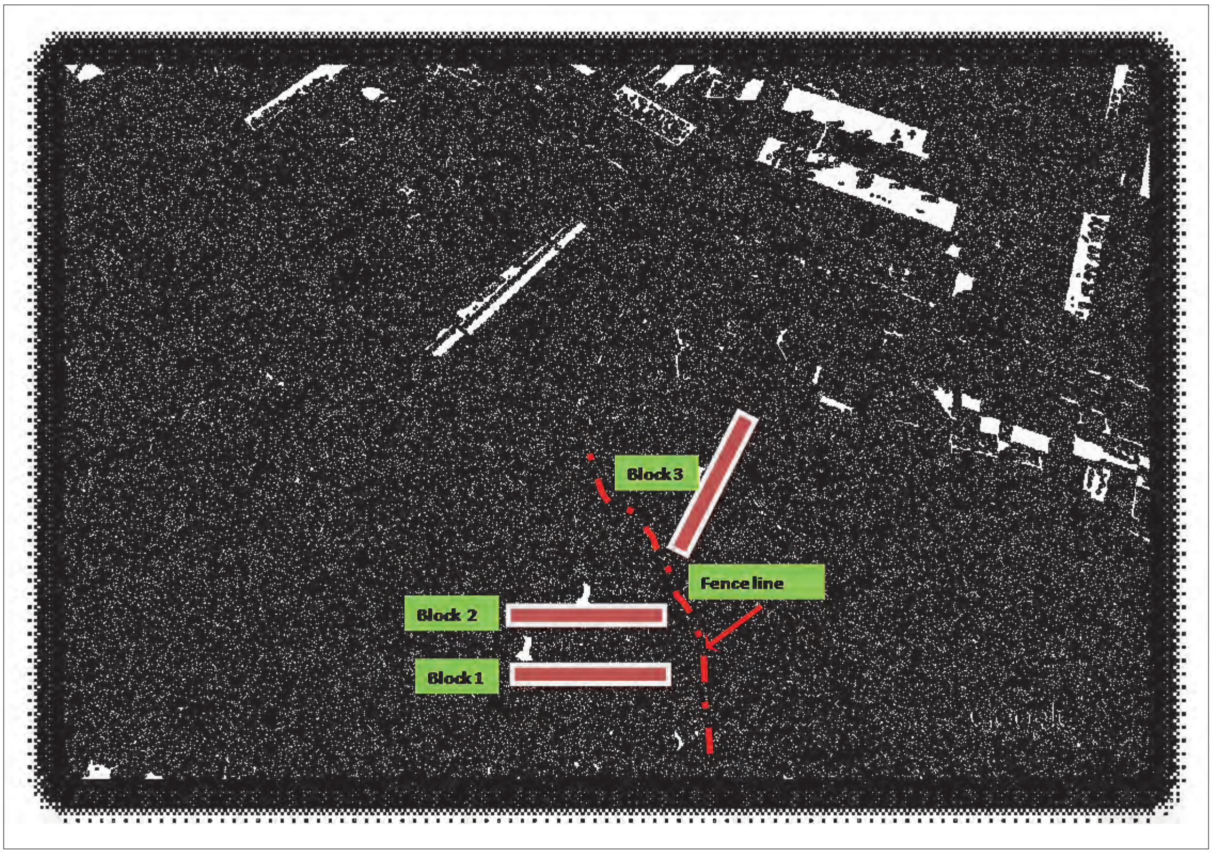


Figure 3.41 The controlled sludge experiment set at three locations (red filled rectangles).

Soil samples were obtained from the different sections of the hillslope up to a depth of 120 cm where in most cases shale was encountered. The soil textural analysis (Hydrometer method) results for the selected study sites were: loam (0-120 cm) for Block 1, clay loam (0-65 cm) overlying silty clay (65-120 cm) for Block 2, and sandy clay (0-75 cm) overlying sandy clay loam soils (75-105 cm) for Block 3. These variations in soil types allow studying the impact of soil textural type on nutrient migration within and out of the sludge burial pits.

3.6.1 Experimental design

The experimental site was divided into three blocks based on a north-south gradient of changing soil textural type and slope.

The general technique used at the study site comprised adding a measured depth of sludge (250 or 500 mm) to a hand dug pit (1.2 m deep x 1.0 m square). Each pit was then backfilled to produce a cover soil layer of 300 mm deep, effectively sealing the sludge underground. One control pit at each of the three blocks contained no sludge. Sludge application rates were randomly assigned.

Three sets of five pits (a total of fifteen pits) were excavated by hand in three designated blocks (Fig. 3.42). Two types of lower boundary conditions were established (six of the pits have drainage capture and drainage system, while the other nine pits have no drainage capture and drainage systems.

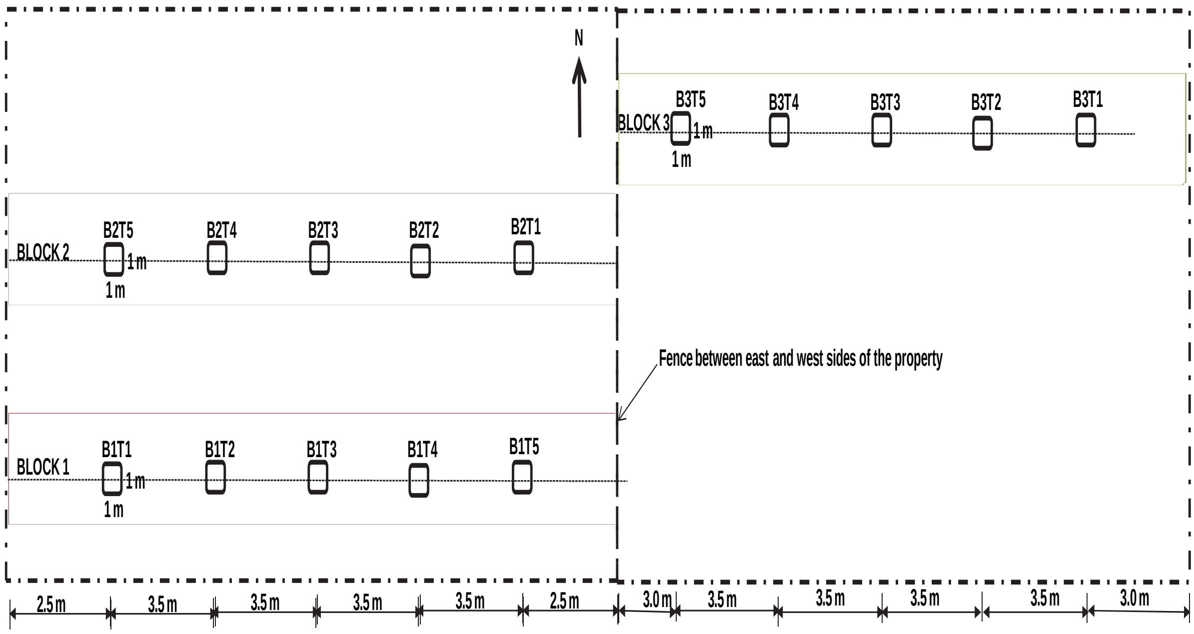


Figure 3.42 Positions of hand dug pits (B1T1-B1T5, B2T1-B2T5 and B3T1-B3T5) for the sludge entrenchment experiment.

The notation e.g. B1T1- stands for Treatment 1 in Block 1. In each of the three blocks T1 and T3 represent pits with 500 mm depth of sludge, T2 and T4 represent pits with 250 mm depth of sludge, and T5 represents a pit with no sludge.

A drainage capture and drainage system (Fig. 3.43) was built for each of the six pits (B1T1, B1T2, B2T1, B2T2, B3T1 and B3T2) to facilitate drainage from these pits. Pans were constructed from stainless steel sheets to form a container with a square, open top and sloping underside to deliver soil water to a collection point underneath the pan, which was connected to a drainage sump using a 50 mm diameter PVC pipe of 100o mm long (Fig. 3). The remaining nine pits however have dimensions of 1 x 1 x 1.20 m without

Sludge to a depth of 250mm was placed in six of the pits (B1T2, B1T4, B2T2, B2T4, B3T2 and B3T4) sludge to a depth of 500 mm was placed in the other six pits (B1T1, B1T3, B2T1, B2T3, B3T1 and B3T3). The remaining three pits (B1T5, B2T5 and B3T5) received no sludge. Excavated soil was backfilled in the sequence of removal and at a density as close to the natural bulk density as possible. The collection pans and drainage systems were installed before the start of installation of any soil water equipment or the application of the sludge. This installation process of the pan lysimeter is shown in Figures 3.44 and 3.45.

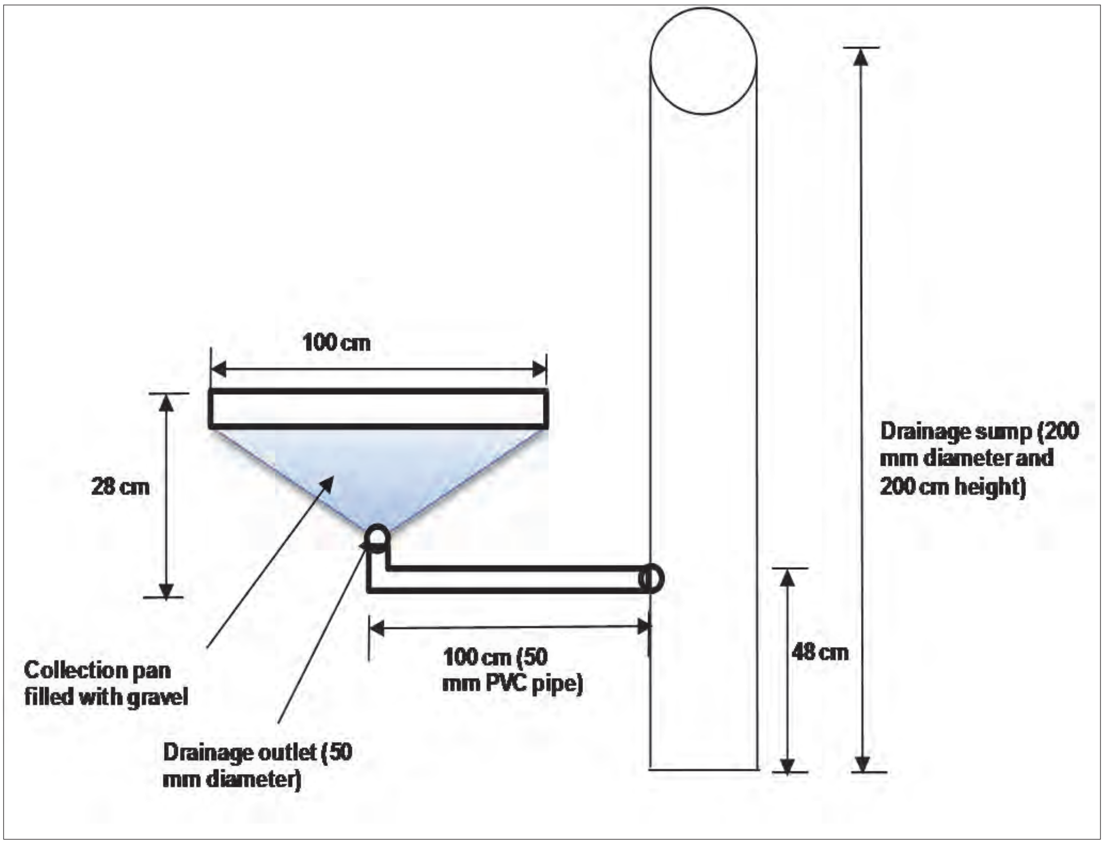


Figure 3.43 Schematic of the detail components of the pan lysimeter – drainage capture and drainage system (dimensions are not to scale).

Figure 3.3.44 Marking (a) and digging of pits (b).

Figure 3.45 Installing pan lysimeter into a pit (a), refilling back the soil (b) and filling 80 mm thick layer of gravel (10 mm dia.) into a pan of 1m wide by 1m long, and a bidim covering the gravel layer (d) to facilitate drainage and prevent soil sediment from entering a drainage system.

Soil water and groundwater instrumentation

Monitoring equipment was installed within and around each of the pits (Figure 3.46). The equipment comprised:

- Three wetting front detectors (WFDs) at depths 15, 85 and 100 cm (in treatments T1, T3 and T5) to capture soil water flowing due to gravity; and another set of three WFDs at depths 15, 60 and 100 cm (in T2 and T4) below the soil surface.
- Four suction lysimeters to collect water either flowing due to gravity or resident in the soil profile under and around each pit as follows: at 15 cm in the top soil cover (in T1-T4), at 60 (in T2 and T4) or 85 cm (in T1 and T3) from the soil surface, below the bottom of the sludge; and 100 cm from the soil surface (in T1-T4), below the sludge to monitor migration of nutrient in the vertical direction. Another suction cup was installed to capture a lateral flow at a 15 cm from the side of the pit in the soil profile, positioned at depths 60cm (in T2 and T4) or 85 cm (in T1 and T3), which is the depth equal to the bottom of the sludge in a pit.
- Three to four Watermarks depending on the treatment type to measure soil suction within the pits as follows: at 15 cm in the top soil cover (in T1-T4), at 40 cm (in T2 and T4) or at 40 and 70 cm (in T1 and T3) from the soil surface, in the sludge; and at 100 cm from the soil surface (in T1-T4), below the bottom of the sludge.
- Three to four Time Domain Reflectometers (TDR) to measure soil water content within and around the pits were installed as follows: at 15 cm in the side wall of the top soil cover (in T1-T4), at 40 cm (in T2 and T4) or at 40 and 70 cm (in T1 and T3) from the soil surface, in the sludge; and at 100 cm from the soil surface (in T1-T4), below the bottom of the sludge but on the side-wall of the soil profile.

Soil core samples were collected at four different depths from each of the three experimental blocks to evaluate the water retention characteristics and hydraulic conductivity of the soil.

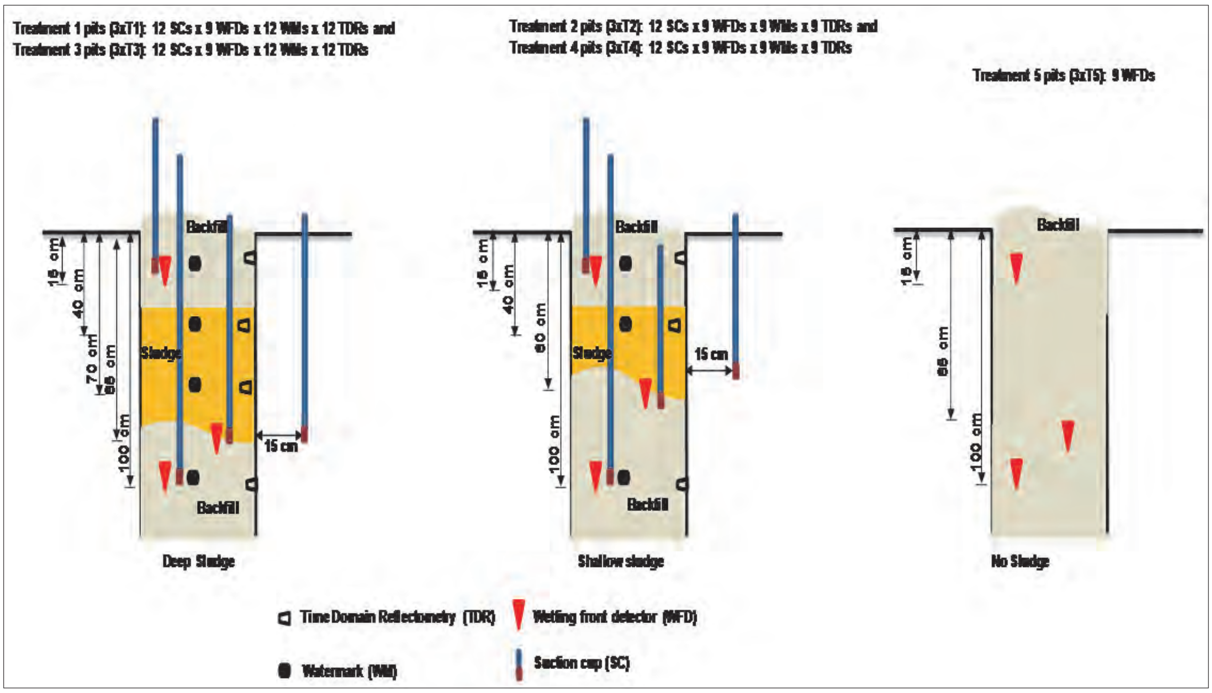


Figure 3.46 Schematic installation layout of the different soil water equipment in pit.

The Wetting Front Detectors (WFDs) and Time Domain Reflectometers (TDRs) were installed as the sludge pits were being filled (Fig.3.47). The Suction lysimeters and Watermarks were installed after all the pits were filled and levelled (Fig. 3.48a). The ceramic cup of suction lysimeters and the Watermarks were soaked in distilled water for 24 hours before installation.

Figure 3.47 Installations of WFD and TDR and the subsequent weighing and filling of the sludge into the pit.

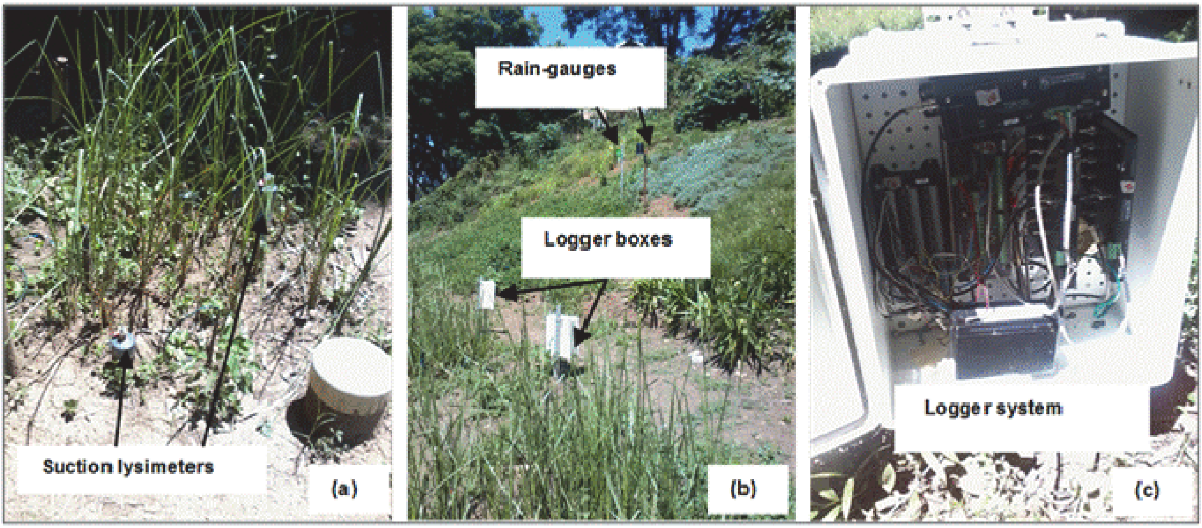


Figure 3.48 Installed suction lysimeters (a), rain-gauge (b), and logging equipment (c).

In the study site, a tipping bucket rain-gauge was installed (Fig. 3.48b) to collect rainfall data over the experimental period. A manual rain-gauge was also installed to collect rain water samples for chemical and isotopic analysis. The water content (TDR) and soil suction (Watermark) measurements are being logged using a CR-10x logger (Fig.3.48c).

3.6.2 Sludge Characteristics and Application

The sludge currently used for this study is sourced from the Howick Wastewater Treatment Plant in Pietermaritzburg. The amount of sludge (wet Mg) equivalent to the application depths used in this experiment (250 or 500 mm) was weighed and filled in each pit (Fig.3.47b).

Sludge samples were collected from each treatment pit during sludge application to the pits for establishing the baseline analyses of both physical and chemical properties of the sludge. The percent solid was determined by evaporating a sample of known volume sludge to dryness in an oven at 105 ^{0}C for 1 hour. 1:5 soil-to-water suspensions were analysed for pH using a pH/ORP/Temperature tester, electrical conductivity (EC) using EC/TDS/Temperature tester, and ammonium, nitrate, phosphate, and chloride on the Thermo Scientific Gallery analyser using a spectrophotometer method.

Planting vetiver grass

Vetiver grass (*Vetiveria zizanioides*) is commonly used in treating wastewater or leachate generated from landfill due to its high capacity of removal of nutrients, particularly nitrogen and phosphorus in wastewater (Truong and Hart, 2001; Zheng *et al.,* 1997). In this study, vetiver (10 cm high above ground and 10 cm deep root) was planted along the rows within each pit at approximately 150 mm spacing between each plant giving a total of 48 plants per square metre (Fig. 3.49). The objective of planting vetiver grass in this study is to evaluate plant nutrient removal from the pits and to protect the pits from soil erosion.

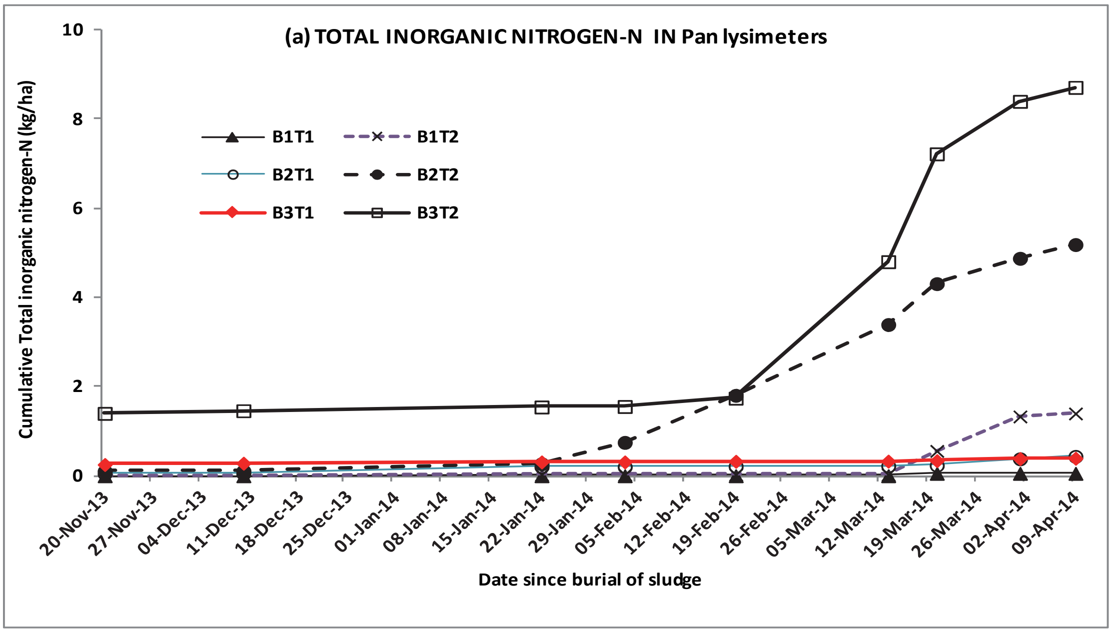
Figure 3.49 Vetiver grass about three months after planting.

3.6.3 Results

The full findings from this work will be published separately. However, all that need be covered here are the results to date from the leachate which has reached the pan lysimeters.[6]

[6] Note that the instrumentation placed alongside the pits has not detected any sideways movement of leachate, which means that the leachate that is caught in the pans is the total of all the leachate.

Water samples collected by pan lysimeter have been analysed for inorganic phosphate (PO_4), nitrate (NO_3) and ammonium (NH_4) concentrations. At the same time the drainage water collected by each pan lysimeter has been measured. The product of the (PO_4, NO_3 and NH_4) concentrations and the corresponding drainage water volumes measured in the pans provides the cumulative inorganic nitrogen (NH_4+NO_3)-N and phosphate-P leached values over the monitoring period (Fig. 3.50). These cumulative values are expressed per hectare assuming sludge is entrenched on only 8% of the land area.



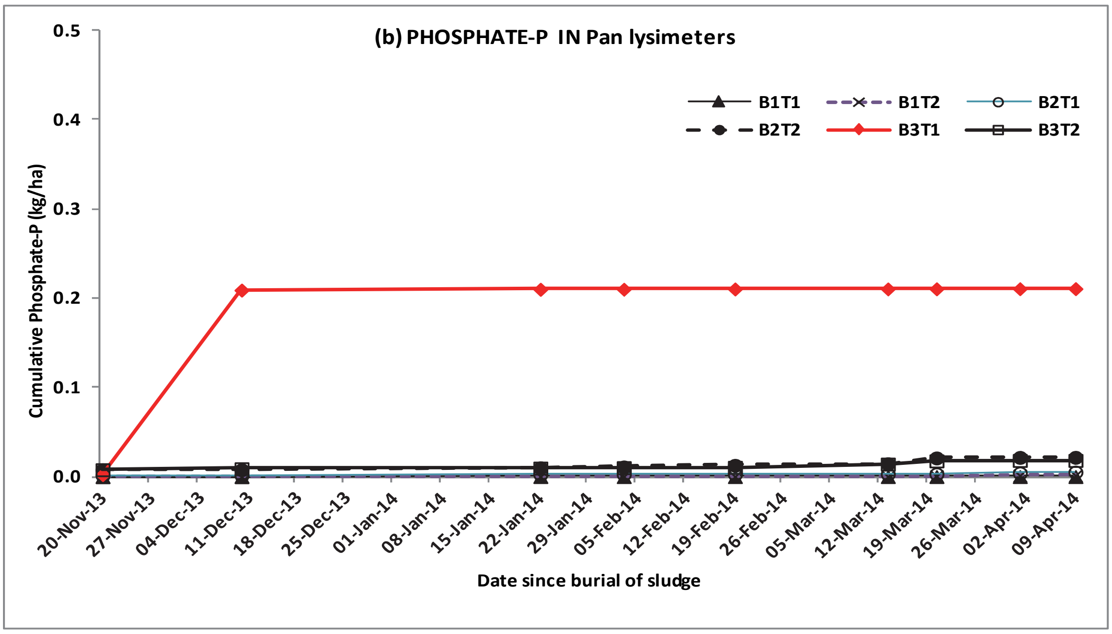


Figure 3.50 Cumulative inorganic nitrogen (NH_4+NO_3)-N (a) and Phosphate-P (b) leaching in the drainage water for the PL with Deep (T1) and shallow (T2) sludge depths installed at different experimental blocks representing different soil types.

In most of the cases the total inorganic-N leaching were observed to increase with time. The measurements during the monitoring period showed that inorganic-N leached from the 250 mm depth of sludge was higher than the inorganic-N leached from the 500 mm sludge depth. Similar trends were observed for the inorganic P-leaching except in the Treatment 1 (T1) of block 3. This seems counter intuitive but is explained by the sludge acting as a sponge which retains water and therefore reduced leachate volumes.

Table 3.7 below shows the inorganic N and P leached into the pan lysimeters between 20 Nov 2013 and 30 September 2014 measured as a percentage of the total N and P contained within the added sludge. The cumulative leached values (kg N/ha or Kg P/ha) were divided by the total N and P applied to the pits during the entrenchment period and expressed as a percentage. The results show that the highest N-leaching was observed in Treatment 2 of block 3 (0.42%). P-leaching was highest in Treatment 1 of block 3 (0.02%).

Table 3.7 Total inorganic nitrogen (NH_4^++NO_3^-)-N (a) and phosphate PO_4^{-2}-P (b) leached into the pan lysimeter installed within 750 mm below sludge pits for different soils (B1-B3) after 10 months of monitoring.

(a)

	B1		B2		B3	
Parameter	**T1**	**T2**	**T1**	**T2**	**T1**	**T2**
Applied Kg- Total N/m^2	4.81	1.82	4.93	1.88	3.56	1.70
leached-Kg (NH_4^++NO_3^-)-N/m^2	0.0019	0.0028	0.00046	0.0064	0.00079	0.0072
% N-leached	0.04	0.15	0.01	0.34	0.02	0.42

(b)

	B1		B2		B3	
Parameter	**T1**	**T2**	**T1**	**T2**	**T1**	**T2**
Applied Kg-Total P/m^2	1.87	0.70	1.91	0.73	1.38	0.66
leached-Kg PO_4^{-2}-P/m^2	9.0E-06	1.4E-06	5.1E-06	1.1E05	2.2E-04	1.6E-05
% P-leached	0.00	0.00	0.00	0.00	0.02	0.00

Table 3.7 also shows that the average percentage of Nitrogen leached from the 500 mm sludge depth (T1 treatments) is 0.023%, while the average percentage of Nitrogen leached from the 250 mm sludge depth (T2 treatments) is 0.303%. In other words increasing sludge depth has not (at least after 10 months) increased the environmental impact but reduced it, insofar as nitrogen leaching is concerned. This seems counter-intuitive, but is explained by the reduced leachate volume collected below the thicker sludge layers (the sponge effect, absorbing moisture).

The P fraction which has leached out is just 0.003% on average, and was zero for five of the test pits. No conclusions can be drawn from the data regarding the influence of sludge depth.

Discussion of the environmental impact is moot as the percentages are very low, and it is doubtful whether these small amounts being leached would travel far beyond the point at which they were detected, which is less than 0.5 metres below the sludge.

After the sludge has been monitored for another 8 months it will be dug up and analysed for the residual N and P content. At this point it will be possible to carry out a mass balance to work out how much nitrogen has leached out of the sludge, and how much has returned to the atmosphere through a process of nitrification and denitrification.

The Sappi trial discussed in Section 3.5 above indicated that after three years the nitrogen levels in the sludge were indistinguishable from those in the surrounding soil. It is probable that the nitrogen degradation process happens faster when the sludge is fresh. It therefore seems significant that during the first wet season when the sludge is at its freshest and when there is rain which could produce leachate, such very amounts of leachate have been detected.

A rainfall simulator is now being used to artificially extend the rain season. This will be done in two wet/dry cycles each one month long, and then the site will be left undisturbed until the advent of the 2014 spring and summer rains, which typically commence by October.

In concluding the discussion of these results it is well to note that the work of Kays et al. (2007), referred to in Section 2.1 of this report, came to similar conclusions.

4. DISPOSAL OF SLUDGE BY BURIAL – THE RISKS

4.1 Introduction

The most commonly perceived risk regarding the burial of faecal sludge is that it will contaminate the groundwater with pathogens and with nitrates, phosphate and other chemical compounds. This perception is prevalent partly because every person schooled in environmental health will have read the story of how John Snow traced the source of a London cholera outbreak in 1849 to a public well which was contaminated from a nearby cesspit (box). The famous Broad Street Pump in Soho was however separated by just one metre from a cholera contaminated cesspit, which is about as "worst case" a scenario as one can conceive. The reality is that most viruses and bacteria which cause disease in humans and other mammals do not survive long outside of the body, while the more hardy pathogens such as helminth ova (worm eggs) are very large relative to soil particles and will remain where they are buried until they eventually die.

Nitrogen is the most common element in the atmosphere and is fundamental to all life processes. Through mostly biological action nitrogen moves between the air and soil and any excess in nitrogen is dealt with by nitrifying and denitrifying bacteria (Figure 4.1). Where soil has high permeability (e.g. coarse sands and gravels) and where there is a lot of groundwater flow then some nitrogen will be lost from the soil as ammonium, nitrite or nitrate in the leachate.

Phosphorus is not particularly mobile in soil, tending to bond with minerals and clay particles (Figure 4.2). Again, with high flows some phosphorus will leach out of the soil.

Box 2: John Snow and the founding event of epidemiology

Snow was a sceptic of the then-dominant miasma theory that stated that diseases such as cholera and bubonic plague were caused by pollution or a noxious form of "bad air". The germ theory of disease had not yet been developed, so Snow did not understand the mechanism by which the disease was transmitted. His observation of the evidence led him to discount the theory of foul air. He first publicised his theory in an 1849 essay, *On the Mode of Communication of Cholera*, followed by a more detailed treatise in 1855 incorporating the results of his investigation of the role of the water supply in the Soho epidemic of 1854.[7]

By talking to local residents he identified the source of the outbreak as the public water pump on Broad Street. Although Snow's chemical and microscope examination of a water sample from the Broad Street pump did not conclusively prove its danger, his studies of the pattern of the disease were convincing enough to persuade the local council to disable the well pump by removing its handle. This action has been commonly credited as ending the outbreak.

Snow later used a dot map to illustrate the cluster of cholera cases around the pump. He also used statistics to illustrate the connection between the quality of the water source and cholera cases. He showed that the Southwark and Vauxhall Waterworks Company was taking water from sewage-polluted sections of the Thames and delivering the water to homes, leading to an increased incidence of cholera. Snow's study was a major event in the history of public health and geography. It is regarded as the founding event of the science of epidemiology.

Snow wrote:

On proceeding to the spot, I found that nearly all the deaths had taken place within a short distance of the [Broad Street] pump. There were only ten deaths in houses situated decidedly nearer to another street-pump. In five of these cases the families of the deceased persons informed me that they always sent to the pump in Broad Street, as they preferred the water to that of the pumps which were nearer. In three other cases, the deceased were children who went to school near the pump in Broad Street...

With regard to the deaths occurring in the locality belonging to the pump, there were 61 instances in which I was informed that the deceased persons used to drink the pump water from Broad Street, either constantly or occasionally...

The result of the inquiry, then, is that there has been no particular outbreak or prevalence of cholera in this part of London except among the persons who were in the habit of drinking the water of the above-mentioned pump well.

I had an interview with the Board of Guardians of St James's parish, on the evening of the 7th inst [7 September], and represented the above circumstances to them. In consequence of what I said, the handle of the pump was removed on the following day.

—John Snow, *letter to the editor of the Medical Times and Gazette*

Researchers later discovered that this public well had been dug only three feet from an old cesspit, which had begun to leak fecal bacteria. The nappies of a baby, who had contracted cholera from another source, had been washed into this cesspit. Its opening was originally under a nearby house, which had been rebuilt farther away after a fire. The city had widened the street and the cesspit was lost. It was common at the time to have a cesspit under most homes. Most families tried to have their raw sewage collected and dumped in the Thames to prevent their cesspit from filling faster than the sewage could decompose into the soil.

from http://en.wikipedia.org/wiki/John_Snow_(physician)

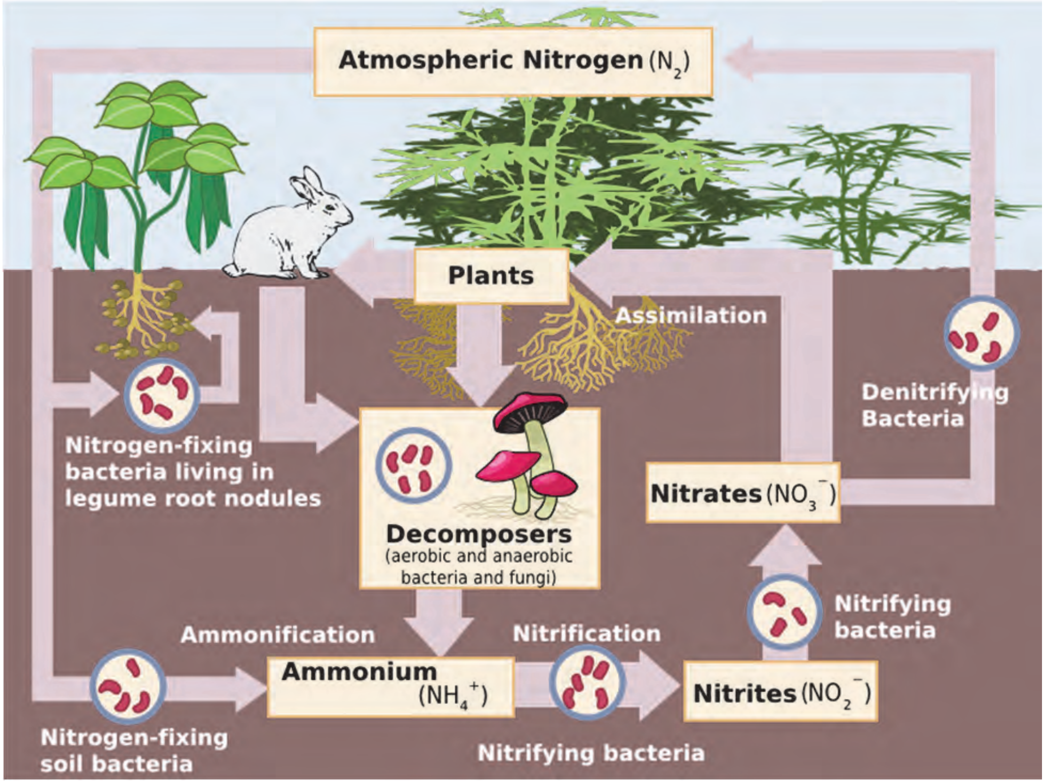


Figure 4.1 The Nitrogen Cycle
(from http://upload.wikimedia.org/wikipedia/commons/f/fe/Nitrogen_Cycle.svg)

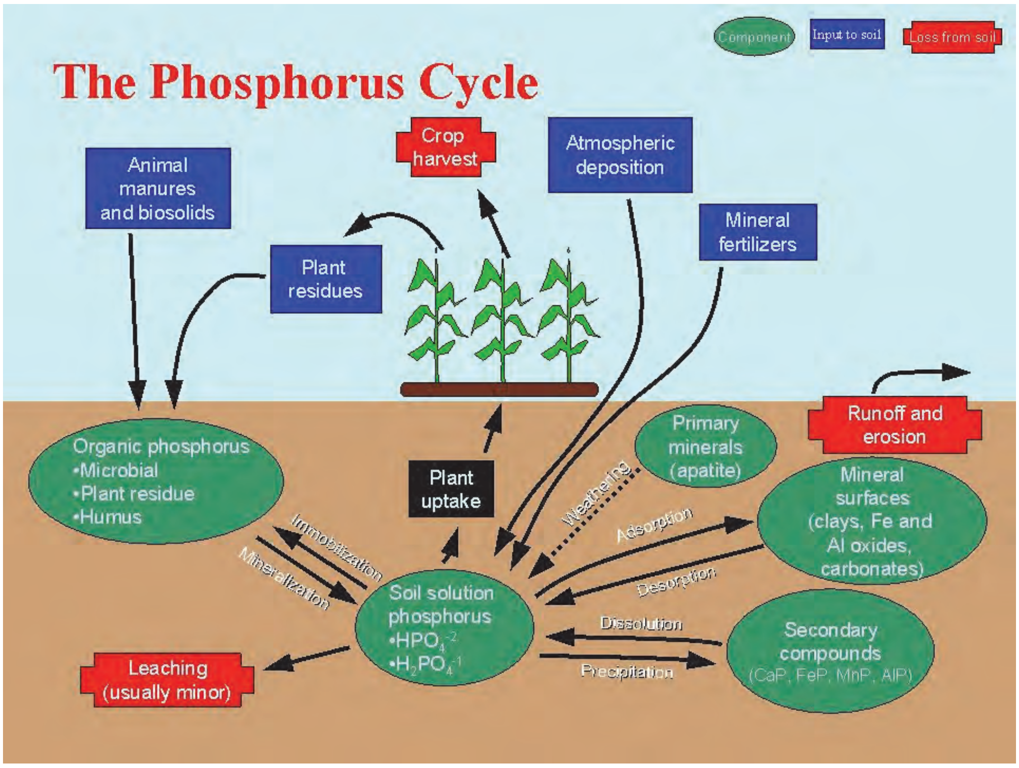


Figure 4.2 The phosphorus cycle, which is more complex than the nitrogen cycle
(from http://www.pgm-blog.com/the-role-of-phosphorus-in-life-processes/

4.2 Groundwater pollution

In 1998 a study was conducted in Ivory Park (a newly established informal settlement in Johannesburg) by van Ryneveld, Fourie and Palmer (2014) to examine the common perception that on-site sanitation will inevitably cause pollution. The study found that movement in the unsaturated zone of bacterial indicators, nitrogen and phosphorus from low flush on-site sanitation systems in low-income areas is very limited, as long as the effluent remains in the subsurface (i.e. does not emerge on the surface). They found that in as little as 2-3 m, the levels of contaminants are no different to background levels and that the impact of the on-site sanitation systems in terms of COD appears to be negligible, with substantial treatment apparently taking place within the soakaway or within the immediate vicinity thereof. They also found that the rate of decrease of the contaminant concentrations in the vertical direction was slightly steeper than the rate of decrease in the horizontal direction. Alternatively, the movement of contaminants was slower in the vertical than in the horizontal direction.

The results of their study are not confined to this particular sanitation system, but can be considered to have more general application to other low flush systems, such as the Asian-style pour-flush latrine and dry on-site sanitation systems, such as the ventilated pit latrine (VIP). By virtue of the higher hydraulic loading, these results provide an upper bound for contaminant movement from dry on-site systems under similar conditions.

The key issue in the handling of wastewater and pit latrine sludge is to design the disposal solution so that potential risks to groundwater are minimal, even if things go badly wrong. Suitable precautions include keeping volumes going to the receiving environment small, ensuring that the receiving environment is not within a sensitive location and that it is not located upslope of a groundwater abstraction point. Due regard must be given to the fact that groundwater is particularly sensitive to the cumulative effect of small impacts (Saayman, 2005).

The unsaturated zone plays an important role in the attenuation of the movement of contaminants and this is most effective in the upper soils layers, where biological activity is greatest. The reduction of contaminants in the unsaturated zone is a function of the rate of flow, the type of contaminant and the capacity of the media to absorb contaminants, e.g. through filtration. Clayey soils reduce the rate of flow and absorb contaminants and a gravelly medium allows rapid movement and minimal absorption of contaminants. However, sandy soil, although highly permeable with a low absorption capacity, is often able to create conditions that form an effective barrier for the movement of contaminants through the sand layer. Shallower trenches therefore allow greater opportunity for absorption in the saturated zone and less risk of contamination of groundwater. Addition of an organic medium, such as sawdust, should increase the opportunity for absorption and, by absorbing water, decrease the flow rate into the soil, which will then allow for more time for pathogenic organisms to die off before water can potentially pollute groundwater. It is important too that surface water is protected from contamination by avoiding spillage of sludge on the ground or burying at too shallow a level, or having the trench at a level where rainwater can wash the sludge out of it and possibly carry contaminants away with it.

The vulnerability of the underground water source is related to the distance that the contaminant must flow to reach the water table, and the ease with which it can flow through the soil and rock layers above the water table (DWAF, 2003).

4.3 Risk of infection from pathogens in sludge

A significant percentage of faecal sludge is comprised of harmless strains of *E. coli* and other bacteria which populate the human digestive tract and assist with the processing and absorption of food. Some of these bacteria assist with the further decomposition of the faecal material after it has been deposited in the pit. The fresh faeces of a healthy individual contains in the order of 100 000 faecal coliform bacteria *per gram*, none of which are harmful.

Depending on the health of the users, faecal sludge can however contain high concentrations of excreted pathogens which include bacteria, viruses, protozoa and helminths. Pathogens which are transmitted by the faecal-oral route and may be found in faeces include:

- Bacteria: *Shigella* (Bacillary dysentery/Shigellosis), certain strains of *E. coli* (*Eschericha coli*), salmonella, typhoid and cholera
- Viruses: Rotovirus, Hepatitis A & E
- Protozoa (parasitic): Giardia, Amoeba (*Entamoeba Histolytica*)
- Helminths (intestinal parasitic worms): e.g. *Ascaris lumbricoides* (roundworm), *Trichuris trichiura* (whipworm), *Necator americanus* and *Ancylostoma duodenale* (hookworm)

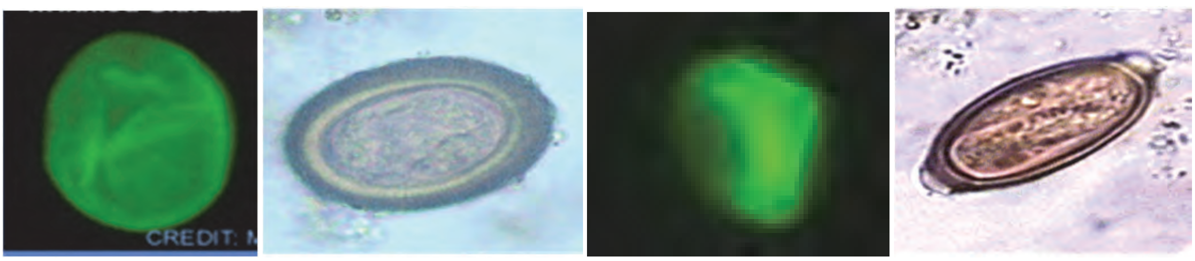


Figure 4.3 Helminths commonly occurring in faecal sludge, from left *Giardia*; *Taenia sp.*; *Cryptosporidium*; *Trichuris trichiura*

In South Africa, *Ascaris, Trichuris* and *Taenia* are the most prevalent parasites infecting people, with sludge samples extracted from latrines located in densely populated slums often revealing massive parasite loads. An investigation into helminthic and protozoan parasites conducted by the University of KwaZulu-Natal (PRG, 2008) based on samples from VIPs used by 120 households indicated that:

- 10% of samples had no parasites
- 60% had *Ascaris*
- 55% had *Giardia*
- 50% had Trichuris
- 21% had *Cryptosporidium*
- 11% had *Taenia*; and
- 60% had either *Cryptosporidium* or *Giardia*

In 2002, IWMI and SANDEC calculated rates for pathogen die-off in faecal sludge. The rates at which various pathogens die off are affected by variables such as ambient temperature – with more rapid die off in warmer climates – and drying, which also promotes die off.

Table 4.1 Pathogen survival periods in faecal sludge (according to IWMI & SANDEC, 2002)

Organism	Average survival time in wet faecal sludge at ambient temperature (days)	
	Temperate climate (10-15°C)	Tropical climate (20-30°C)
VIRUSES	<100 days	<20 days
BACTERIA:		
salmonellae	<100 days	<30 days
cholera	<30 days	<5 days
faecal coliforms	<150 days	<50 days
PROTOZOA:		
Amoebic cysts	<30 days	<15 days
HELMINTHS:		
Ascaris eggs	2-3 years	10-12 months
Tapeworm eggs	12 months	6 months

Ascaris lumbricoides – the common round worm – is used as a "marker" for safe re-use or disposal of human biological waste because the eggs of this parasite are extremely hardy and outlive most other pathogens (e.g. bacteria and viruses).

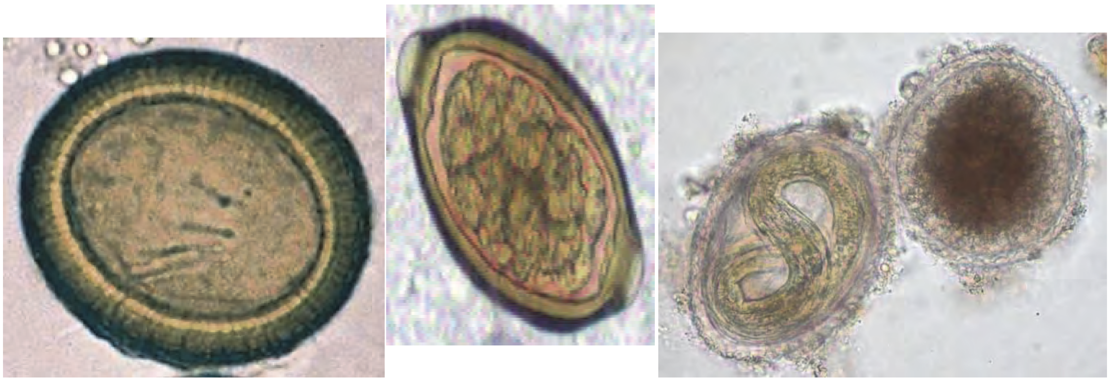


Figure 4.4 Some of the stages of development of *Ascaris l*. in the faecal-oral cycle of transmission Left: The hard shell of the ovum allows it to survive outside a human host; centre: necrotic ovum in the process of dying; right: fertilised egg with motile larva about to hatch.

In a study carried out by UKZN on sludge removed from pit latrines the lowest measured *Ascaris* egg count was 142 per gram of sample (wet weight) (142 eggs/g w.w.) and the largest was 3937 eggs/g w.w. with most of the samples analysed showing a total ovum count of between 200 and 1000 eggs/g w.w.. Of these eggs, the average viability per sample varied between 20 and 40%. The high variance of the measurements (a common characteristic of this kind of measurement) resulted in large confidence intervals. None of the samples were free from *Ascaris* eggs. The pit sample size was small (only 10 pits, and all from the same community); however, the high load of eggs indicates that ascariasis (roundworm) must have been rife in the community during the time of sampling and for a significant period of time before that.

In terms of health risk assessment, a sludge may be allocated a binary classification as infective or not-infective. Thus, if there are a detectable number of undeveloped ova, ova with motile larvae or ova with immotile larvae per gram of sludge, it may be concluded that the sludge should be treated as infective.

Observations from Umlazi sludge burial site

Work carried out during Project K5-1829 indicated that pathogens buried in soil die off over a period of two to three years. Figure 4.5 below is from the final report for Project K5-1829 (Figure 5.56, page 71).

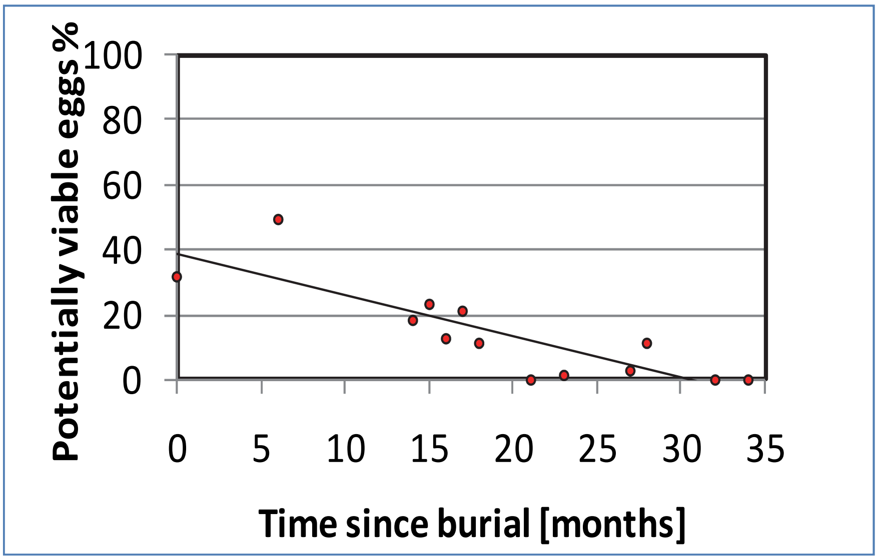


Figure 4.5 Die-off of Ascaris over the first 30 months of burial at the Umlazi site

In January 2013 (between 40 and 50 months after burial) 88 new samples were taken from the Umlazi experimental site. Of these 30 were taken from pit sludge, 28 were taken from the ground surface where the sludge had been buried and 30 were taken from the ground surface in the vicinity of the experimental site as a control. The purpose behind each of these three sets was as follows:

Sludge samples: to determine if any pathogens had survived in the sludge itself

Ground surface: to determine if the ground surface where the sludge had been buried posed a public health risk

Background surface: As a control for comparison with the ground surface above the sludge

The samples were analysed by Colleen Archer and Val Kelly at the School of Biological Sciences for *Ascaris*, *Trichuris Trichiura* and *Taenia.* The full results are included in Appendix D. Hawksworth and Foxon have previously observed that fresh VIP sludge in Durban typically contains 200 to 1000 Ascaris ova per gram. In the 30 sludge samples analysed, only 1626 *Ascaris* ova were observed in a total of 300 g of sludge (vs the 180 000 that might have been there at the time of burial based on the 200 to 1000 range (i.e. a 100 fold reduction). Of these 1626 ova, only one was observed to be motile, and the rest were undeveloped, immotile, infertile, necrotic or dead (with 11% being necrotic and 87% being dead). Given that the experimental method might have introduced ova from the surface as the pits were dug, this evidence suggests that pathogens in buried sludge definitely do die off within 3 to 4 years. As there would be no need or intention to dig up the sludge after burial, it can by extension be concluded that burial is a safe means of sludge disposal as far as pathogens are concerned.[7]

Pathogens in surface soil

A further 28 samples were taken from the soil surface in the area where the sludge was buried. The soil surface is of more interest from a public health point of view, as this is where the public might be exposed to the risk of infection. Due to the low counts of ova, 20 gram samples were analysed. From the 28 samples a total of 75 *Ascaris* ova were recovered from the 560 g of soil, 72 of which were dead and 3 were necrotic. In one of the samples 752 possibly viable *Taenia* (tapeworm) ova were observed. However, given that *Taenia* ova do not normally survive in the open for this length of time, it is likely that these ova were deposited subsequent to the burial of the sludge.

The 30 background surface samples displayed similar results to the surface samples taken from the area where the sludge was buried. A total of 47 *Ascaris* ova were recovered from 600 g of soil, of which 47 were dead and 10 necrotic. These results are not significantly different from the *Ascaris* incidence detected in the surface soil where the sludge was buried. This indicates that the *Ascaris* that is observed on the surface where the sludge was buried is representative of the area in general, and is therefore not necessarily the result of the sludge burial operations.

Observations from Sappi site

Further pathogen testing was done at the Sappi site in March 2013. Twenty soil samples were taken from the surface or near the surface within the experimental site and twenty from above the site and alongside the site (Figure 3.37 refers). The purpose was to check to what extent the intervention of burying sludge on the experimental site had increased the presence of helminth ova relative to the surrounding background level.

The samples were analysed by Colleen Archer and Val Kelly at the School of Biological Sciences for *Ascaris*, *Trichuris Trichiura* and *Taenia.* The full results are included in Appendix D. Note that all Trichuris and Taenia were dead – the numbers merely indicate the numbers of dead ova observed. The classification of the *Ascaris* ova were split as follows: undeveloped, motile, immotile, infertile, necrotic or dead.

The total count of ova from Transect F (within the experimental site) came to 90 of which 57 were *Ascaris*, 3 *Trichuris* and 30 *Taenia*. It is notable that 23 or 77% of the *Taenia* came from just one sample. Six of the *Ascaris* were motile, 7 immotile, 11 were necrotic and 33 were dead.

The total count of ova from Transect G (outside the side) came to 17 all of which 17 were *Ascaris*. Five of the *Ascaris* were necrotic and 12 were dead.

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[7] This conclusion does not include sludge infected with viruses (much smaller than bacteria and helminths) buried in coarse sand or gravel close to a groundwater abstraction point, but no sludge should be disposed of in such a location.

Transect F (within the experimental site) had five times the number of ova relative to Transect G. Although the numbers are small (for example in fresh VIP sludge in Durban researchers typically find up to 1000 Ascaris ova per gram of feaceal sludge) the difference between F and G is nevertheless noticeable.

5. DISPOSAL OF SLUDGE BY BURIAL – PRINCIPLES, COSTS AND BENEFITS

5.1 Introduction

During the course of the five different experiments which are described in Section 3 of this report, something has been learned about the methods, costs and benefits of sludge entrenchment.

5.2 First Principles

Sludge derived from on-site sanitation and from wastewater treatment plants contains valuable nutrients. However, adding nutrients to a site beyond the agronomic rate (the rate at which plants can use the nutrients) will not result in increased plant growth[1]. On the evidence of the trials described in this report, any surplus potassium and phosphorus contained in the sludge will remain in the soil and will thus enrich the site for the long term. Any surplus nitrogen will, however, return to the atmosphere within a few years and will not have any lasting benefit.

Due to its high moisture content sludge can be expected to settle substantially after burial. Therefore if the intention is to have the sludge layer commence 300 mm below the surface the trench should be filled to, say, 100 mm below the surface and then the excavated material should be heaped on top of the trench to provide the 300 mm cover.

The fine root system whereby trees derive their nutrients are located near the surface where such elements are normally to be found in the richer topsoil layers. For the greatest benefit, therefore, the sludge should be buried in shallow and not deep trenches. Shallow trenches are generally quicker to dig, especially if manual labour is used. A further advantage of a shallow trench is that the soil that is displaced and brought to the surface will have a higher topsoil fraction than is the case with a deep trench. If one digs very deep trenches, say 1.5 or 2.0m, and fills them with sludge, a problem is what to do with all the (often clayey or stony) subsoil material which has been brought to the surface.

It is impossible to bury sludge in timber plantations using machinery without having to dig up a lot of tree stumps (unless it is a greenfield site, which in forestry is very unusual). Sludge entrenchment in a forestry application should therefore be done using a labour intensive approach.

In a different application, say sugar cane, a more plant-intensive approach may be more suitable.

A question that comes up when dealing with sludge entrenchment is whether or not lime should be added to the sludge at the time of burial. Quicklime (Calcium Oxide, CaO) has for many years been spread over carcasses to prevent putrefaction and to reduce or eliminate odours. This has particularly been practiced in places and at times where normal burial has not been possible. The lime does not speed the decomposition of the carcass, but in fact retards or even arrests it altogether. Under normal circumstances one wants to allow natural processes to follow their course, and therefore there is no reason to add lime. Where the additional of lime and particularly quicklime can be useful is in stabilizing sludge to render it pathogen free. The addition of 20% to 40% of quicklime to the sludge by mass, combined with thorough mixing, will result in an exothermic

[1] For a discussion on the use of organic sources of plant nutrients in agriculture, see Appendix B.

reaction as the Calcium Oxide combines with moisture in the sludge to form Calcium Hydroxide ($CaOH_2$). With the addition of enough quicklime and enough mixing the temperature will be raised high enough for long enough to kill the pathogens. The addition of quicklime in these quantities and in the correct manner will however not only be a complicated and hazardous process, but it will also be expensive, obviating the economies of a simple burial process.

5.3 Costs of burial

With trenches 3 metres apart, 100 m long, 300 mm wide by 400mm deep with a 300 mm sludge depth, one can bury 297 m^3 of sludge in one hectare. If the nitrogen content is 2% of the dry mass, if the sludge density is 1.3 tons/m^3 and if the moisture content is 60%, this would equate to some 3 088 kg of nitrogen per hectare. Depending on a variety of factors the normal agronomic rate would be closer to 100 kg/ha, so this rate of sludge application is well over the amount that the trees can use. However, the economic driver for sludge burial is to save on the costs of alternative disposal options (such as landfill).

A typical task rate for excavation by labour in ordinary pickable soil is 3 m^3/day. If one assumes a daily wage of R120, then the cost of the excavation will be R4/metre or R13 333 per hectare. A further R6 667 should be added for the backfilling of the trenches. The cost for excavation and backfill in 2014 prices using manual labour and typical productivity rates can therefore be expected to be approximately R20 000 per hectare or R67 per m^3 of sludge. This excludes the cost of transporting the sludge.

Transport costs

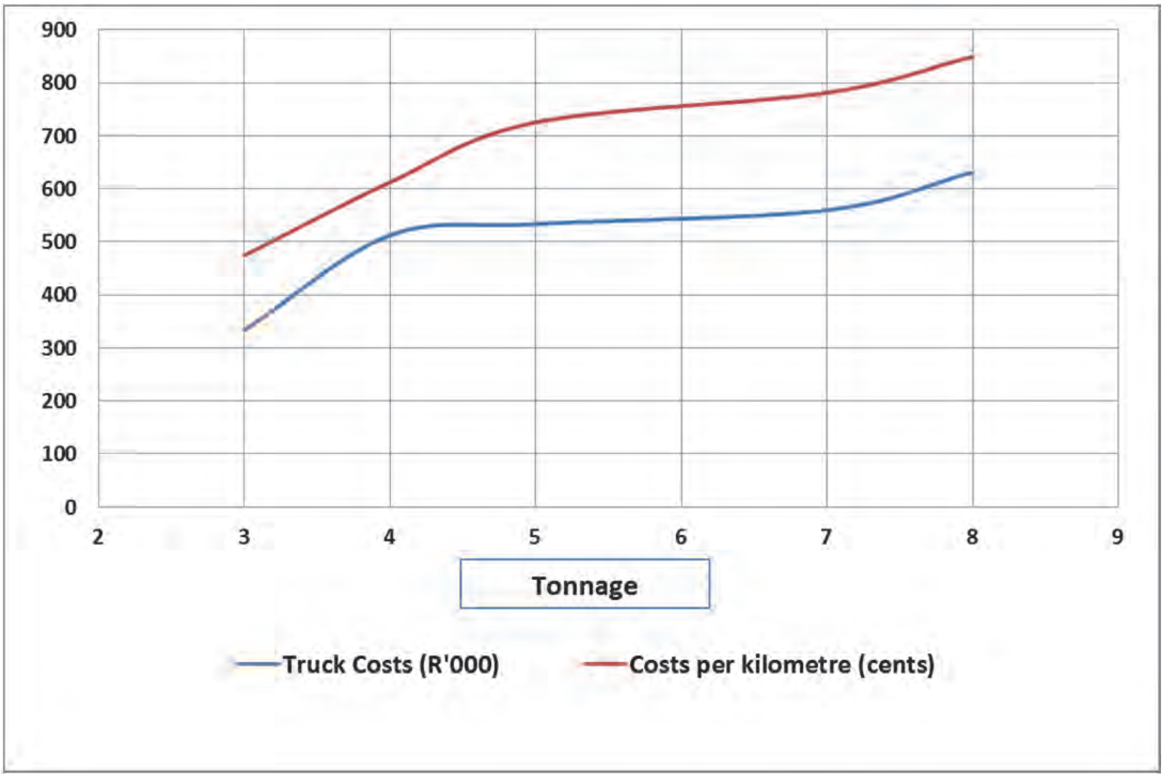

Figure 5.1 Costs of operating trucks (adapted from KZN Department of Agriculture, 2010)

From Figure 5.1 it can be seen that a 7 ton truck is more cost effective than a smaller truck. Owning and operating a 7 ton truck, assuming it travels on average 50 000 km per year, will cost in the order of R8/km (escalated from KZN Department of Agriculture, 2010). Assuming the truck returns empty from the disposal site the cost of haulage is calculated using the return distance, so the above cost must be doubled – i.e. R16 for every kilometre of distance between the point where the sludge is collected to the point where the sludge is disposed. Assuming the truck is loaded with 5 m^3 of sludge (6.5 tons) the cost per m^3.km for transporting sludge will be R3.20/m^3.km. If one assumes that the distance from the collection site to the disposal site is 30 km, the long haulage cost will be R96/m^3.

To this must be added the short haul cost. The sludge has to be tipped in heaps around the perimeter of the area where it is to be buried. From there using plant or labour it must be collected and placed in the trenches. For this operation plant will be cheaper than labour, but it is not always practical to use plant (e.g. on forestry sites which are full of tree stumps). If labour is used and if the average short-haul distance is 100 metres, then a further R40/m^3 should be allowed to load the sludge into wheelbarrows, wheel it to the trench and offload it (each m^3 will require 20 wheelbarrow loads).

The transport cost for 297 m^3 of sludge – the amount that can be disposed of in a hectare – can therefore be estimated at R28 512 for long haul (assuming 30 km travel one way) and R11 880 for short haul.

So the cost to bury 297 m^3 sludge assuming that the collection point is 30 km from the disposal point will be approx. R60 392, or R203 per m^3.

Costs which have not been included in the above analysis include the loading of the sludge at the collection point and the cost of meeting environmental authorization requirements at the disposal site.

5.4 Benefits from sludge burial

The Mean Annual Increment (MAI) refers to the average growth a tree or stand of trees have exhibited up to a specific age. The MAI of Eucalyptus in South Africa is in the 15 to 25 ton/ha.annum range (water, sun and soil dependent). After a number of years, the MAI decreases and it then makes economic sense to harvest the timber and start a new growth cycle.

South African timber growers typically harvest after 10 years growth[2], with tonnage approximately 200 tons per hectare. The Net Standing Value (NSV – the value after deducting harvesting, haulage and milling costs) of Eucalyptus in South Africa is typically in the range of R250-R350/tonne. This means that the NSV after 10 years is approximately R60 000/ha.

The Sappi sludge entrenchment trials have indicated that a 50% increase in the timber volume is the probable effect of the added nutrients. This would translate into an extra R30 000/ha, which is only half the cost of the sludge entrenchment derived in section 5.3 above, assuming that as much as 300 m^3 of sludge is disposed of per hectare.

[2] In colder climates such as North America the harvest cycle can be as long as 30 to 40 years.

The question is, what is the alternative? Composting could be attractive if there is a ready source of organic waste which can be mixed with the sludge, but it is not cheap and quality control may be hard. Surface application is limited to Class A sludge only, and is further limited to favourable topography and hydrology. Where composting is not viable and where surface application is not considered suitable, sludge is typically buried in landfills.

Section 7 deals in more detail with alternative sludge disposal methods. The ballpark cost for most of these alternatives is in the R500/m^3 range. This means that, even though disposal of sludge by entrenchment is likely to cost in the order of R200/m^3 and it is unlikely that this will result in a benefit exceeding R100/m^3, this is still a lower cost and better return than is typically achieved with the alternatives.

6. DISPOSAL OF SLUDGE BY BURIAL – LEGAL REQUIREMENTS

6.1 Introduction

Unfortunately no large scale application of sludge entrenchment will be able to go ahead without an Environmental Impact Assessment and the necessary authorisations. This section will explain the process and the implications.

6.2 An overview of applicable legislation

South African environmental legislation is complex and typically authorisation by more than one government department needs to be obtained. The Department of Water Affairs and Sanitation (DWAS), Department of Environmental Affairs (DEA), Department of Health (DoH) and the Department of Agriculture (DoA) all have a regulatory role to play in the beneficial use of sludge (Herselman & Moodley, 2009c).

The Environmental Impact Assessment (EIA) Regulations under the National Environmental Management Act (NEMA) (Act No. 108 of 1998) work on the basis of lists of activities with various thresholds that may or may not trigger the need for an EIA. This will be discussed in more detail in Section 6.2.4. Whether or not there is a requirement for an EIA, however, there is still a responsibility to comply with other relevant legislation.

One of the requirements of the EIA Process is that, early in the process, all legislation and guidelines relevant to the activity need to be considered and it must be demonstrated that this has been done. The relevant legislation with regard to disposal of faecal sludge will therefore be covered briefly. These include:

- Constitution of South Africa;
- National Environmental Management Act (NEMA) (Act No. 108 of 1998);
- Municipal Systems Act (Act No. 32 of 2000);
- National Environmental Management Act (Act No. 59 of 2008);
- National Water Act (Act No. 36 of 1998);
- Conservation of Agricultural Resources Act (Act No. 43 of 1983) (CARA);
- National Health Act (Act No. 61 of 2003) (HA);
- Water Services Act (Act No. 108 of 1997) (WSA);
- Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (Act No. 36 of 1947); and
- National Environmental Management Waste Act (Act No. 59, 2008)

6.2.1 Relevant definitions

The Waste Act (Act No. 59 of 2008) defines hazardous waste as "...any waste that contains organic or inorganic elements or compounds that may, owing to the inherent physical, chemical or toxicological characteristics of that waste, have a detrimental impact on health and the environment..."

The Department of Water Affairs publication entitled, "Minimum requirements for the handling, classification and disposal of hazardous waste" (DWAF, 1998), has a more detailed classification of hazardous waste, namely:

"...an inorganic or organic element or compound that, because of its toxicological, physical, chemical or persistency properties, may exercise detrimental acute or chronic impacts on human health and the environment. It can be generated from a wide range of commercial, industrial, agricultural and domestic activities and may take the form of liquid, sludge or solid. These characteristics contribute not only to degree of hazard, but are also of great importance in the ultimate choice of a safe and environmentally acceptable method of disposal.

Further to this, a Hazardous Waste can be defined as a waste that directly or indirectly represents a threat to human health or the environment by introducing one or more of the following risks:

- explosion or fire;
- infections, pathogens, parasites or their vectors;
- chemical instability, reactions or corrosion;
- acute or chronic toxicity;
- cancer, mutations or birth defects;
- toxicity, or damage to the ecosystems or natural resources;
- accumulation in biological food chains, persistence in the environment, or multiple effects to the extent that it requires special attention and cannot be released into the environment or be added to sewage or be stored in a situation which is either open to air or from which aqueous leaching could take place."

Therefore, due to the potential presence of *infections, pathogens, parasites or their vectors*, faecal sludge is regarded as a Hazardous Waste and must be treated as such. Obviously, the degree of hazard associated with it will depend on its origin and to what extent it is broken down and this should be addressed appropriately. Depending on the degree of stabilisation sludge can be declassified as hazardous waste.

6.2.2 The Constitution of South Africa

The Bill of Rights (Constitution of South Africa, Act No. 108 of 1996) gives all South Africans the right to an environment that is "not harmful to their health or well-being", as well as the right to have the environment protected for the benefit of present and future generations. This must be balanced against the need to promote and sustain "justifiable economic and social development". The constitution further requires co-operative governance between the different spheres of government, so, in this instance, the Department of Water Affairs and Sanitation and other departments would be expected to cooperate with municipalities to address the problem of disposal of faecal sludge.

6.2.3 Municipal Systems Act

In terms of the Municipal Systems Act (Act No. 32 of 2000), municipalities are required to go through an Integrated Development Planning (IDP) process to prepare a five-year strategic development plan for the area under their control. Municipalities are obligated to prevent pollution and ecological degradation, to promote conservation and secure ecologically sustainable development and use of natural resources. If disposal of faecal sludge is to be part of their waste management strategy, the details of this should be included in the IDP.

6.2.4 NEMA EIA Regulations

The National Environmental Management Act (NEMA) (Act No. 108 of 1998) provides the framework for the sustainable management and protection of the environment.

Environmental Impact Assessment Regulations under NEMA list activities in three Listing Notices which may trigger the need for an Environmental Impact Assessment. Listing Notice 1 (No. R.544) includes activities that would require ("trigger") undertaking of a Basic Assessment, Listing Notice 2 (No. R.545) lists activities that would require a Scoping process followed by a full Environmental Impact Assessment, and Listing Notice 3 (No. R.546) includes activities specific to different Provinces that would require a Basic Assessment.

There are no activities in Listing Notice 1 that have relevance to handling or disposal of faecal sludge. Activities in Listing Notices 2 and 3 may apply, depending on the scale of the proposed facility.

Listing Notice 2 (Scoping and Environmental Impact Assessment required).

Activity 5: The construction of facilities or infrastructure for any processes or activity which requires a permit or license in terms of national or provincial legislation governing the generation or release of emissions, pollution or effluent and which is not identified in Notice No. 544 of 2010 or included in the list of waste management activities published in terms of Section 19 of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008), in which case that Act will apply.

Listing Notice 3 (Province specific – Basic Assessment required).

Activity 10: The construction of facilities or infrastructure for the storage, or storage and handling, of a dangerous good, where such storage occurs in containers with a combined capacity of 30 but not exceeding 80 cubic metres.

(a) In Eastern Cape, Free State, KwaZulu-Natal, Limpopo, Mpumalanga and Northern Cape provinces:

i. In an estuary;

ii. Outside urban areas, in:

(aa) A protected area identified in terms of NEMPAA [National Environmental Management Protected Areas Act], excluding conservancies;

(bb) National Protected Area Expansion Strategy Focus areas;

(cc) Sensitive areas as identified in an environmental management framework as contemplated in chapter 5 of the Act and as adopted by the competent authority;

(dd) Sites or areas identified in terms of an International Convention.

(ee) Critical biodiversity areas as identified in systematic biodiversity plans adopted by the competent authority or in bioregional plans;

(ff) Core areas in biosphere reserves;

(gg) Areas within 10 kilometres from national parks or world heritage sites or 5 kilometres from any other protected area identified in terms of NEMPAA or from the core areas of a biosphere reserve;

(hh) Areas seawards of the development setback line or within 1 kilometre from the high water mark of the sea if no such development setback line is determined;

(ii) Areas on the watercourse side of the development setback line or within 100 metres from the edge of a watercourse where no such setback line has been determined;

(jj) Within 500 metres of an estuary.

iii. In urban areas:

(aa) areas zoned for use as public open space;

(bb) Areas designated for conservation use in Spatial Development Frameworks adopted by the competent authority or zoned for a conservation purpose;

(cc) Within 500 metres of an estuary.

6.2.5 Waste Act, 2008

With respect to the handling of faecal sludge, the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) is particularly relevant.

Government Notice 718 lists waste management activities in respect of which a waste management licence is required in accordance with section 20(b) of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008).

The definition of "facility for a waste management activity" contained in the Government Notice 718 "...means a place, infrastructure, structure or containment of any kind, wherein, upon or at, a waste management activity takes place and includes a waste transfer station, container yard, landfill site, incinerators, lagoons, recycling and composting facilities".

Government Notice 1113 of 2010 lists waste management activities in respect of which a Waste Management Licence is required in accordance with Section 20(b) of the National Environmental Management Act (Act No. 59 of 2008). Any activity listed under Category-A of that notice requires authorisation by means of a Basic Assessment and any activity listed under Category-B of that notice requires authorisation by means of a full Environmental Impact Assessment process, as stipulated in the EIA regulations made under section 24(5) of the National Environmental Management Act, 1998 (Act No. 107 of 1998).

Category-A

With regard to storage of faecal sludge, the following Category-A activities may apply, depending on volumes to be dealt with (numbering as in the Notice):

Activity 2: The storage including temporary storage of hazardous waste at a facility that has the capacity to store in excess of 80 m^3 of hazardous waste at any one time.

Activity 8: The recycling of hazardous waste in excess of 500 kg, but less than 1 ton per day.

Activity 16: The reuse, treatment, processing or disposal of animal waste at a facility with a capacity to reuse, treat, process or dispose of animal waste in excess of 1 ton per day.

Activity 17: The reuse, treatment, processing or disposal of sludge from a wastewater treatment facility with a capacity to reuse, treat, process or dispose of sludge in excess of 10 tons of general sludge or any quantity of hazardous sludge per day.

Activity 18: The construction of facilities for activities listed in Category-A of this schedule (not in isolation to associated activity).

Category-B

With regard to storage of faecal sludge, the following Category-B activities may apply, depending on volumes to be dealt with:

Activity 2: The reuse and recycling of hazardous waste in excess of 1 ton per day.

Activity 3: The recovery of hazardous waste, including the refining, utilisation or co-processing of hazardous waste at a facility with a capacity to process more than 1 ton of hazardous waste per day, excluding recovery that takes place as an integral part of an internal manufacturing process within the same premises.

Activity 5: The treatment of hazardous waste using any form of treatment at a facility that has the capacity to treat in excess of 1 ton of hazardous waste per day.

Activity 9: The disposal of any quantity of hazardous waste to land.

Activity 11: The construction of facilities for activities listed in Category-B of this schedule (not in isolation to associated activity).

Depending on the nature and scale of the operation, a Waste Licence may be required. On-site storage of sludge should be avoided, but, if it is not possible and it is to be stored for more than 90 days, the area would be considered a disposal area and a disposal permit would be required.

Subject to confirmation from the National Department of Environmental Affairs, if Wastewater Treatment Works sludge is channelled to a composting facility and it amounts to less than 10 tons per day, then no EIA process needs to be undertaken. This is on the understanding that stabilised and dewatered WWTW sludge is no longer classified a hazardous waste. On the other hand, if sludge from pit latrines (which is still classified a hazardous waste) is to be similarly processed, then the threshold would be less than 500kg per day. In the case of the uMngeni WWTW in Howick, for example, where 6 tons per day needs to be processed, all of the sludge can therefore be composted without the need to undergo the EIA process and, in the case of rural pit latrines, the sludge from a few homesteads in close proximity to one another could be emptied into a single trench, onto which trees can be planted.

The key issue which would affect the implementation of entrenchment for disposal of pit latrine sludge, is that this sludge should not be accumulated into a central facility for disposal because this would start to trigger other activities listed under the Waste Act. Since the class of sludge from pit latrines is not predictable, it makes sense to steer away from composting and to rather implement entrenchment. On the other hand, sludge emanating from a smallish WWTW (< 10 tons sludge per day), such as in Howick, can be tested on a regular basis and therefore could be composted quite safely, with the proviso that the compost derived from this is not sold to the general public, but rather used by nurseries and landscapers for planting of trees and non-food plants.

A discussion of the legal requirements for beneficial use of sludge is contained in Part 3 of Herselman and Moodley (2009c).[3]

There is currently confusion within the National Department of Environmental Affairs about the application of the Regulations under NEMA and the Waste Act with respect to faecal sludge and informed guidance and/or a formal response is needed from the key roleplayers, i.e. the National Department of Environmental Affairs, the Department of Water Affairs and the Department of Health, with regard to interpretation of the current legislation (Snyman, 2012).

6.2.6 National Water Act (1998)

The National Water Act (Act No. 36 of 1998) was promulgated in 1998 to provide for fundamental reform of the law relating to water resources, to repeal certain laws and to provide for matters connected therewith. The most important result of promulgation of the National Water Act was that it changed the status of groundwater from a private resource to a public resource. This coincided with a greater recognition of the importance and role of groundwater as a water supply source and in sustaining ecosystem function (Saayman, 2005).

Chapter 2, Part 4, of the Water Act deals with pollution prevention, and in particular the situation where pollution of a water resource occurs or might occur as a result of activities on land. The person who owns, controls, occupies or uses the land in question is responsible for taking measures to prevent pollution of water resources. If these measures are not taken, the catchment management agency concerned may itself do whatever is necessary to prevent the pollution or to remedy its effects, and to recover all reasonable costs from the persons responsible for the pollution.

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[3] However, note that this document refers to the EIA Regulations in terms of the Environment Conservation Act (Act No. 73 of 1989), which have been superseded by the EIA Regulations in terms of the National Environmental Management Act (NEMA) (Act No. 108 of 1998).

van Ryneveld, Fourie and Palmer (2014) found that movement in the unsaturated zone of bacterial indicators, nitrogen and phosphorus from low flush on-site sanitation systems in low-income areas is very limited, as long as the effluent remains in the subsurface (i.e. does not emerge on the surface). In as little as 2-3 m, the levels of contaminants are no different to background levels. This finding would apply to sludge entrenchment, but it would still be incumbent on the person implementing the technique to ensure that there is no risk of contamination of underground aquifers or leaching into streams or other water supplies.

6.2.7 The Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act

According to the Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (Act No. 36 of 1947), a fertiliser can only be classified as an organic fertiliser if it contains less than 20 % ash and 40 % water. Sludge does not comply with these criteria and cannot formally be classified as an organic fertiliser, even though it does contain major plant nutrients (calcium, magnesium, potassium, phosphorus and nitrogen), essential micronutrients (zinc, copper, molybdenum and manganese), and does improve the physical properties of soil. Indeed if sludge has been treated to eliminate pathogens, a wide range of agricultural applications would be possible.

6.3 Due process – what will be required

An Environmental Impact Assessment (EIA) is defined as the process of identifying, predicting, evaluating and mitigating the biophysical, social and other relevant effects of development proposals, prior to major decisions being made. It is a tool to aid decision making, in the same way that any new project would be subject to a cost-benefit analysis or an analysis into the technical feasibility of the project. An EIA could stop a project if it shows that the environmental costs far outweigh the economic benefits. However, the EIA process is not designed or intended to impede economic development and nor is it the sole means to implement environmental conservation.

The EIA process under NEMA will entail either a Basic Assessment or a Scoping and Environmental Assessment:

> A <u>Basic Assessment</u> applies to activities listed in Listing Notices 1 and 3 of the NEMA Environmental Impact Assessment Regulations. These are smaller-scale activities, the impacts of which are generally known and can be easily managed. Typically, these activities are considered less likely to have significant environmental impacts and, therefore, do not require a highly detailed Environmental Impact Assessment.
>
> A Basic Assessment Report (BAR) is a more concise analysis of the environmental impacts of the proposed activity than Scoping and EIA Reports. However, Basic Assessment still requires public notice and participation, consideration of the potential environmental impacts of the activity, assessment of possible mitigation measures, and an assessment of whether there are any significant issues or impacts that might require further investigation. The Basic Assessment Report must provide the Competent Authority (assessing authority) with enough information to consider the application and to reach a decision. If the Competent Authority is unable to decide, based on Basic Assessment Report alone, the Competent Authority may request an Applicant to subject the proposed activity to the more thorough Scoping and EIA process.

While the term "basic" is used relative to a full EIA, it is by no means a trivial exercise. The BAR process can take anything from four months to two years to complete, and typically costs anywhere from R50 000 to R200 000.

Scoping and EIA requires a thorough environmental assessment for activities contained in Listing Notice 2. Activities in this list are those activities that (due to their nature and/or extent) are likely to have significant impacts that cannot be easily predicted. They are therefore higher risk activities that are associated with potentially higher levels of pollution, waste and environmental degradation.

A Scoping Report (including Plan of Study) requires: a description of the proposed activity and any feasible and reasonable alternatives; a description of the property and the environment that may be affected and the manner in which the biological, social, economic and cultural aspects of the environment may be impacted upon by the proposed activity; a description of environmental issues and potential impacts, including cumulative impacts that have been identified; and details of the public participation process undertaken. In addition, a Scoping Report must contain a "roadmap" for an Environmental Impact Assessment, referred to as the "Plan of Study for the EIA", specifying the methodology to be used to assess the potential impacts, and the specialists or specialist reports that will be necessary.

An Applicant may only conduct an EIA after the Competent Authority has approved the Scoping Report and the Plan of Study for the EIA.

The Scoping and EIA process culminates in the development and submission of the Environmental Impact Assessment Report and the Environmental Management Plan to the Competent Authority.

6.3.1 Identification of Interested and Affected Parties

Public participation is one of the cornerstones of the EIA process. Part of the public participation process involves the advertising of the EIA process in newspapers, but this is insufficient to ensure adequate involvement of stakeholders.

Conservation organisations, such as SANParks and KZN Wildlife, keep lists of Interested and Affected Parties (I&APs) but the details on those lists are frequently out of date and include many I&APs that may have no interest in the proposed project. Therefore it is important that all contact details are confirmed and that the identity of relevant contact people, in the case of organisations, is checked. Proactive identification of potential stakeholders will also be required and public advertisements and word of mouth assists in this identification process.

If the entrenchment of faecal sludge is to be considered as an option adjacent to communities, with the goal being to provide communities with fruit-bearing trees or trees to enhance quality of life, the communities should be involved in the process and educated as to both the risks and the benefits, so that, firstly, they do not perceive that they are being used as a dumping ground for other people's waste and, secondly, that they buy into the process and take active measures to protect and nurture the trees.

Implementation of sludge entrenchment in small quantities adjacent to small communities will probably not require the undertaking of an EIA process, as long as thresholds are not exceeded. However, this should not exclude consultation with, and education of, communities.

Key organisations that should be consulted in any EIA process involving disposal of faecal sludge include:

(a) the Department of Water Affairs (DWA).
(b) the Local Catchment Management Agency.
(c) the Local municipality.
(d) the Department of Health.
(e) the provincial conservation department.
(f) Community organisations and representatives.
(g) Neighbouring landowners.

6.3.2 Identification of Alternatives

An essential component of the EIA process is the consideration of alternatives and these have to be clearly described in any EIA document. An assessment of the impacts associated with these alternatives is also required. Some of the alternatives to sludge entrenchment would include:

1. Surface application of sludge.

   Surface sludge application has been shown to provide plant nutrients, enhance soil productivity and improve soil properties. However, offensive odours and perceptions of health and environmental problems limit the widespread application of this method and it is only allowed for Class A1a sludge.

2. Disposal at landfill sites.

   Landfill sites ultimately reach capacity. Due to the lack of conveniently located open space and the "not in my backyard" syndrome which affects all development but particularly landfills, it is becoming increasingly difficult to find new sites. Moreover to meet regulations the cost of construction is high. By disposal of sludge in landfills, there are only costs and risks and no benefits whatsoever.

3. Composting.

   The easiest treatment of sewage sludge is composting. The organic matter is decomposed to stable humus under the aerobic thermophilic conditions (more than 55 ◦C for 15 days or more), which is enough for heat inactivation. Nevertheless, not all the material is evenly heated and there is a risk of pathogen regrowth (Romdhana *et al.*, 2009).

4. Incineration.

   Opinions vary about whether or not this method will become the preferred option in most European Union countries or if there will be an increased use in agriculture (Alcock, 2009). In the South African situation, this method has nothing to recommend it due to cost and potential air pollution.

6.3.3 Identification of specialist studies required

Depending on the scale of the processing of sludge and whether or not either a Basic Assessment or a full-blown Scoping and EIA process is required, investigations by various specialists will be necessary.

In some senses, it is easier to simply find a specialist to examine every aspect of the proposed activity and produce reams of reports than to be selective about using specialists. It is a case of "more is not better" because there are issues of cost, assessing authority time and capacity constraints, as well as getting bogged down in unnecessary detail. Therefore, it is necessary for the Environmental Assessment Practitioner (EAP) to have insight as to when to involve specialists, how to involve them and what terms of reference to give them. In that sense then, an EAP needs to be a good generalist and have the ability to see the bigger picture and synthesise the essential elements of sometimes complex reports.

Some of the principles in involving specialists in the EIA process include (Saayman, 2005):

1. Eliminate unnecessary specialist involvement through proactive planning and design to avoid or sufficiently reduce negative impacts that may otherwise require specialist assessment.
2. Maximise use of existing relevant information prior to involving a specialist. If the existing information is too complex for the EAP to understand or needs clarification, a specialist can be used simply for that purpose.
3. Involve relevant specialists as early in the EIA process as possible to increase efficiency and effectiveness of their involvement, including identification of key issues, planning, design and mitigation.
4. Maintain continuity of specialist involvement throughout the process.
5. Include the specialist in relevant aspects of the public participation process.

It is important to note that all specialists are required to be independent, which means that they have no vested interest in, and will not benefit financially from, the outcome of project decision making and/or the EIA process.

The EAP, Project Proponent and Specialist must all agree on the terms of reference up front and must all agree on the commonly used (and confused) EIA terms and definitions. In some instances, particularly in the case of complex and/or controversial projects, certain selected stakeholders may need to review the terms of reference as well.

Hydrogeologist

Saayman (2005) makes it clear that input from a hydrogeological specialist would be required for any proposed development that includes the handling, or discharge into the environment, of effluent or chemicals with the potential to change groundwater quality. The level of environmental assessment will be determined by the project scale, sensitivity of the proposed location and expectation of environmental impacts. It is important that the specialist hydrogeological input is sought at the earliest possible stage in the EIA process.

It is expected that a hydrogeological expert will deal with all types of sub-surface water, namely, soil water, interflow (water moving through unsaturated part of the aquifer) and groundwater in aquifers.

Because of the potentially disastrous consequences of pollution of groundwater, the hydrogeologist should be involved in the following aspects of the EIA process:

1. Communication with selected stakeholders.
2. Identification, consideration and possible design of alternatives.
3. Identification of all potentially significant direct, indirect and cumulative impacts, both negative and positive.
4. Identification as to whether or not the proposed development exceeds any legislative guidelines or Resource Quality Objectives (RQO's).
5. The determination of the significance of the impact needs to be considered in the light of the vision for the area, which will naturally include its water resources.
6. Identification of potential beneficiaries and losers.
7. All assumptions, uncertainties and gaps in knowledge must be clearly articulated. If conclusions are formulated based on assumptions, these must be clearly outlined and, where necessary, scenarios must be generated which illustrate their effect on these conclusions.
8. Assistance in the identification of management actions that will reduce the likelihood of negative impacts on the receiving environment and users or reduce the significance. These management actions may take the form of avoidance, mitigation, compensation and offsets, rehabilitation or enhancement.

In the case of disposing of faecal sludge, which has the potential consequence of pollution of groundwater, a conceptual model should be developed, which focuses on understanding groundwater recharge volume and pathways, the chemical character of the sludge and geochemical processes that could alter the chemical character of the sludge. The characteristics and persistence of pathogens also needs to be understood, though this is starting to enter the realm of microbiology, parasitology and public health.

Groundwater-dependent ecosystems depend on a particular volume and distribution of groundwater and they can be significantly altered or changed by the volume, temporal distribution or change in character of the groundwater supply.

The influence of weather conditions, i.e. flood and drought, and other external factors needs to be taken into account.

It is important to note that prior to any activities taking place, the quality of the groundwater should be assessed to establish a baseline and then ongoing monitoring of the groundwater should take place. As time progresses, any other activity that takes place nearby that may affect groundwater should also be included in the equation, so that if pollutants are found in the groundwater, the correct source of pollutants can be identified.

Important issues to take into account during the specialist investigation are the following.

1. Extent of separation between the base of the development and the water table to prevent pollutant entry to the groundwater resource and effect adequate effluent degradation.
2. Characteristics of the soil and rock material and whether or not they allow rapid infiltration of polluted water.
3. Whether there are any boreholes used for extractive use within the area of influence of the proposed development, or whether there are any aquifers that have the potential to become a significant water supply source for a nearby community.

4. Whether or not the underlying aquifer is recognised as particularly vulnerable to pollution.
5. Whether there is a groundwater-dependent ecosystem within 1 km of the development that may be affected by it and suffer a loss of ecological functioning and associated ecosystem services.
6. The specialist needs to be clear on what extent the proposed development could impact on the meeting of Resource Quality Objectives as laid down by the Department of Water Affairs and Sanitation.

There are a number of documents that deal, in detail, with issues associated with disposal of faecal sludge, hazardous materials and protection of groundwater (DWAF 1998a&b and 2003; Herselman *et al.*, 2009a-c; Snyman *et al.,* 2006a&b).

Soil scientist

A soil scientist may be required to evaluate changes brought about by the sludge to the soil in the unsaturated zone.

Microbiologist/public health practitioner

Whilst there is available literature that describes, in detail, pathogens associated with faecal sludge (e.g. Romdhana, 2009), and detailed guidelines for handling of wastewater sludge are available (DWAF, 2006a-e), it would be advisable, for the sake of credibility in the eyes of stakeholders, to have some form of consultation with, or appoint, a microbiologist or public health practitioner as part of the team of specialists assessing any plans to process faecal sludge, especially if it concerns growing any edible crops and/or if sludge is to be buried close to human habitations. In any event, faecal sludge needs to be classified prior to being used beneficially and part of that classification is in terms of microbial parameters (Classes A, B, C), which includes faecal coliforms and number viable helminth ova per unit volume.

Archaeologist, palaeontologist

In some instances, where there may be a risk of disturbing archaeological artefacts, a Heritage Impact Assessment may be required. This will depend on the location, nature and the scale of the proposed development. For example, if the area to be trenched covers more than 1 ha or the trenches are longer than 300 m.

Biodiversity specialist/ecologist

A biodiversity specialist must assess the degree of ecosystem dependence on groundwater and the effects that disposal of faecal sludge may have on plants and animals.

6.3.4 Potential impacts and mitigation measures

Potential impacts emanating from the handling and final entrenchment of faecal sludge can broadly be grouped as follows.

1. Risks to human and animal health.
   a. Transmission of disease.
   b. Transmission of parasites.

   c. Heavy-metal poisoning.
   d. Physical discomfort from unpleasant odours.
2. Pollution of groundwater.
3. Pollution-induced damage/toxicity to plants or animals.

The contaminants associated with faecal sludge may be divided into two groups:

a. *Microbial* contaminants, typically viruses and bacteria, but also including larger organisms like protozoa and helminths (worms).
b. *Chemical* contaminants, consisting of both organic (e.g. human waste) and inorganic (e.g. salts) components. The organic components of primary concern are poisons and those that decay rapidly and form odorous by-products. The inorganic components of primary concern are nitrogen, phosphorus and chlorides (DWAF, 2003).

Research conducted to-date on sludge entrenchment has shown positive results, but there is a need to investigate how the entrenchment technique may be applied under South African conditions and what safe working procedures should be developed to protect health of workers, local communities and the environment. Other trials have focussed exclusively on entrenchment of treated sludge from WWTW, but, in the South African context, VIP toilets are the standard for basic sanitation and it is therefore vital to investigate entrenchment as an option for the beneficial use of pit latrine sludge as well.

In terms of the requirements for Environmental Impact Assessment reporting, when evaluating impacts and proposing mitigation measures, gaps in knowledge and assumptions made need to be clearly articulated, including the possible implications of these. Therefore, it will be important to state, until the matter has been fully investigated, where trials have been done with treated sludge from WWTW as opposed to pit latrines and that the degree of stabilisation and the contents of the pits may vary considerably compared to the relative consistency of sludge from WWTW.

Risks to human health

Public fear of faecal sludge is an important factor that needs to be taken into account, because, without adequate controls, the fear is well-founded. Based on discussions with a number of people during the course of this investigation, smell and the attraction of flies seems to be the biggest single factor influencing public perception of faecal sludge. Once the smell has been taken care of, or in other words, once the sludge has been stabilised, concern drops dramatically and the issue of pathogen loading and presence of pollutants is not really considered by the average person. For example a Merrivale-based compost supplier reported that for some time he was supplying the Boschhoek golf estate with bulk compost and word got around that he used faecal sludge in his compost, in spite of the fact that he did not do so. He nearly lost the contract and had to do some urgent damage control to avert that.

It is interesting to note that in 1998, 54 % of all sludge in the United States was being reused and that a wastewater treatment works is viewed as a “biosolids production” facility, rather than a disposal facility. This use of the word “biosolid” rather than “sludge” changes the emphasis to a resource rather than a waste product (Alcock, 2009).

Whilst the application of sludge entrenchment and planting of trees adjacent to low cost housing developments is an attractive proposition, both in terms of removal of a problematic waste product and in terms of increased food security for inhabitants, there are some practical problems associated with this, which include the following.

1. Temporary storage issues and transport costs could potentially be a major factor limiting the use of entrenchment as a disposal mechanism for faecal sludge, unless sludge is buried close to the source.
2. Material exhumed from pit latrines often contains high loads of infective *Ascaris* ova, as well as quantities of *Taenia* and *Trichuris* ova, and therefore should be regarded as hazardous to those working with sludge. Workers should therefore be educated about the risks. They should also be supplied with gloves, encouraged to wash hands regularly and be de-wormed regularly. Whilst handling the sludge, they should also wear masks. Consideration should also be given to supplying them with overalls and boots and that the overalls are washed at work and this clothing and footwear is never taken home and that they wear clean overalls every day. They should have facilities to shower at work. Precautions should be taken to prevent transmission of pathogens on boots and vehicle wheels to other areas.
3. Depending on the source of the sludge, it is possible that residents in these areas may perceive that they are being taken advantage of and that, because they are poor and “can’t fight back”, they are having other people’s rubbish dumped on them. Therefore, careful public consultation and education about the benefits of sludge entrenchment will be needed.
4. One of the biggest problems that people living in these areas report about planting fruit trees is that goats browse them before they get a chance to establish, so fencing would be required, at least until they grow big enough to be able to withstand browsing. Alternatively, some of the entrenchment could be used specifically to grow trees or shrubs that would serve as fodder for goats. This would have to be quick-growing plants with high nutritional value and that do not pose an alien invasive risk. The best would be a locally indigenous species.

Safety protocols in the event of accidental spillage will be required and “Hazchem” placards would need to be fitted to all vehicles carrying the sludge. All road accidents would need to be reported to Traffic Officials, the Competent Authority and Department of Water Affairs and Sanitation and steps would need to be taken to minimise the impact of any contamination on public health and the environment. The safety protocols should outline these steps in detail and all transport operators and their drivers would need to be familiar with these protocols. Appropriate measures to contain accidental spillage on site would need to be implemented and these would include access restrictions, covering contaminated areas with soil, containment of runoff and protection of workers.

Appropriate measures would need to be considered for unanticipated events like floods and unplanned human settlements and prevention of informal use of the disposal site should be avoided.

Volume 4 of the *Guidelines for utilisation and disposal of wastewater sludge – requirements for the beneficial use of sludge at high loading rates* (Herselman & Moodley, 2009c), discusses the requirements when sludge is to be added once-off to soil at high rate (higher than agronomic rates) to improve its chemical and physical characteristics to enable it to sustain vegetation. It is required that all sludge producers must confirm the classification of the sludge before land application (Herselman & Moodley, 2009c). For the application of sludge entrenchment, restrictions apply mainly to Pollutant Classes b and c and Microbial and Stability Classes are not really an issue, except when handling and transporting.

Discussion

Whether or not either a Basic Assessment or Scoping and EIA are required, it would be good to consult with communities and/or neighbours in the event of either sludge entrenchment or composting taking place.

Whilst the application of sludge entrenchment and planting of trees is an attractive proposition, both in terms of removal of a problematic waste product and in terms of increased production, the practical problems which must be overcome including the hazards of handling a potentially infectious substance, and problems with public perception which may arise.

To put the minds of stakeholders at ease, all uncertainties regarding the application of entrenchment of faecal sludge need to be addressed and the EIA process needs to demonstrate thorough specialist investigations into the nature of the receiving environment and the potential risks to groundwater and human and animal health. These investigations must include the pedology and hydrological characteristics of the receiving sites. Strict protocols to be followed regarding the handling and transport of sludge need to be clearly elucidated and these must be possible to implement and monitor without any high-tech interventions that could break down with inadequately trained operations personnel.

Strict monitoring of soil and groundwater during all stages of the process, from planning, through to construction of facilities (if applicable), implementation and closure, will be required. The extent of this will depend on the extent of the project, volumes and class of sludge being dealt with.

Strict safety protocols and protocols in the event of accidental spillage will be required and appropriate measures should be considered for unanticipated events like floods and the development of unplanned human settlements on the disposal site.

Careful site selection will be absolutely critical and it must be possible to demonstrate, to both the authorities and the public, that all risk factors have been taken into account in the selection of sites. Briefly, these factors include topography, proximity to flood lines, site stability, gradients, distance to fissured rocks less than 3 m below the surface, presence of surface water, areas of groundwater recharge and/or abstraction, permeability of and nature of soils, proximity to settled areas and habitat of endangered species that could be disturbed. Access to the site must be practical and economical and should not, in itself, pose environmental risks.

The nature of the sludge must be known before application and, in the case of wastewater treatment works sludge, the sludge should be analysed prior to each application to determine pollutant loads. This is particularly important to avoid using sludge contaminated with heavy metals if the sludge is used for any edible crops, but is not as important for industrial crops, such as plantation trees.

Detailed guidelines on the handling of sludge and the application of the technique are contained Appendix A and these should be included in any environmental management plan prepared for the disposal of faecal sludge.

7. DISPOSAL OF SLUDGE – SOME ALTERNATIVES

7.1 Introduction

Over one million cubic metres of sludge is produced annually in South Africa from both on-site and waterborne sanitation,[1] and all of this sludge has to be disposed of. Apart from entrenchment, some of the alternative methods (some well-known, others less so) which can be used for sludge disposal are the following:

- Landfill
- Composting
- Surface irrigation
- Surface application
- Pelletisation
- Processing by Black Soldier Fly larvae

This section provides a brief overview of these alternatives.

7.2 Landfill

Waste legislation classifies waste into different types according to risk level, and each of these types requires a different "Class" of landfill design (Table 7.1). Sewage sludge, due to the presence of pathogens and potential chemical contaminants, is typically regarded as having a Moderate Risk requiring a Class A or Class B containment barrier.

Table 7.1 South African landfill classification according to the type of waste disposed of

Waste Risk Level	Disposal Requirements
Type 0: Very High Risk	Disposal **not allowed**. The waste must be treated first and then re-tested to determine the risk profile for disposal.
Type 1: High Risk	Disposal only allowed at a landfill with a **Class A** or **Hh/HH** containment barrier design.
Type 2: Moderate Risk	Disposal only allowed at a landfill with a **Class B** or **GLB+** containment barrier design (or Class A).
Type 3: Low Risk	Disposal only allowed at a landfill with a **Class C** or **GLB+** containment barrier design (or Class B or A).
Type 4: Inert Waste	Disposal allowed at a landfill with a **Class D** or **GSB-** containment barrier design.
Non-hazardous Waste (Pre-classified)	Disposal only allowed at a landfill with a **Class B** or **G S/M/L B-/B+** containment barrier design.

The requirements for Class A and B containment barriers are extensive. Figure 7.1 shows the requirement for a Class B containment barrier, which comprises six different layers which together can be as much as one metre thick.

[1] Based on a population of 50 million people and 20 litres of sludge per person per year. The actual average sludge production per person per year across all processes has not been determined but is likely to be more than 20 litres/person/year.

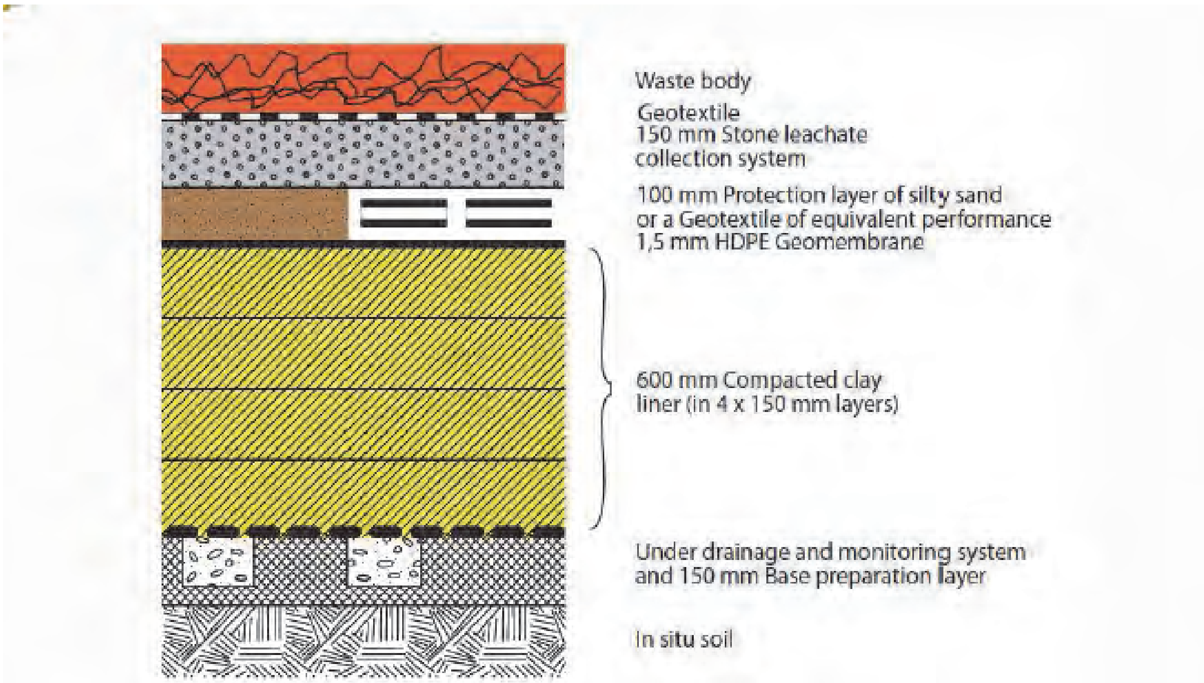

Figure 7.1 Class B Containment Barrier Design

When eventually the landfill runs out of "airspace" the whole area must be capped, and the requirements for this capping are almost as extensive as those for the containment barrier. Landfills also require an engineered drainage system (Figures 7.2 and 7.3), fencing and access roads, and of course, land.

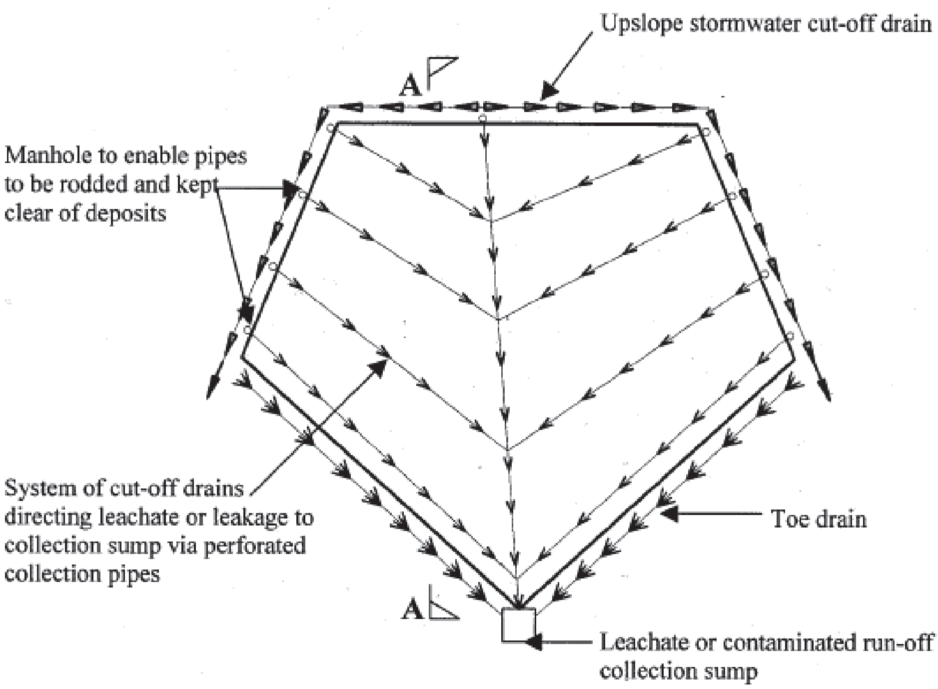

Figure 7.2 Plan of Landfill showing typical drainage systems

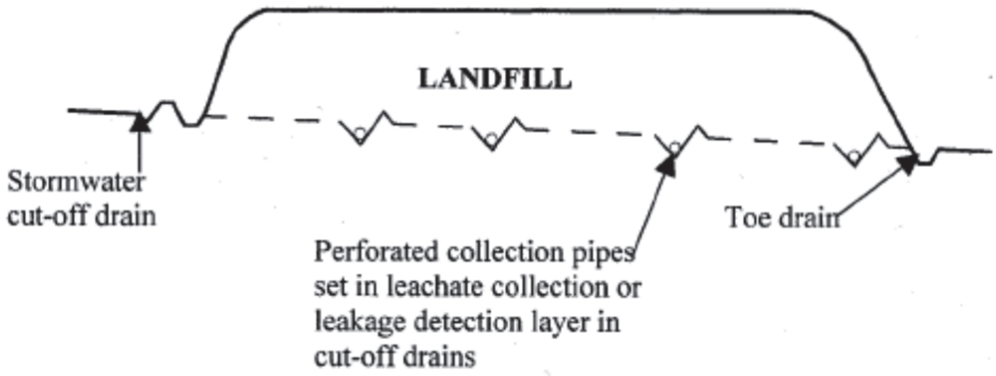

Figure 7.3 Section through a Landfill

The cost of building and operating a landfill varies widely according to the class of the landfill and the topography. Taking everything into consideration, the costs typically range from R200 to R800 per cubic metre of waste, with the latter being the costs for the more expensive Class A type landfills. Table 7.2 below shows how the construction costs for a Type B landfill site are developed.

Apart from the capital and operating costs, it is becoming more and more difficult to find land for new landfill sites, as whichever site is proposed there is generally a strong lobby against the use of that site. Apart from the fill being a potential eyesore, people living near these sites complain of dust (from the soil used for covering the waste), wind-blown trash, and odour. Some landfills self-combust due to the heat generated within them as various types of biodegradable waste within the fill decompose.

Table 7.2 Example of Costs for Developing and Closing a Landfill Site

Note: Operating costs are excluded

Nominal area of cell	4.3	hectares
Depth of cover available	1.0	metres
Volume of cover per cell	42 844	m^3
Potential airspace per cell	214 221	m^3
Efficiency of usage of space	80%	
No. of cells	3	no
TOTAL AREA	16.1	hectares
TOTAL VOLUME	614 400	m^3
AVERAGE TONNES OF WASTE PER ANNUM	50 000	tons
Density of compacted waste	0.75	
Cover to waste ratio	0.2	
Airspace used per annum	80 000	m^3
Cell dimensions		
width	200	m
length	200	m
height	8	m
Side slopes	1:5	
Volume of cell	204 800	m^3

Base area per cell	40 804	m^2
Edge preparation	5%	
Area to prepare per cell	42 844	m^2
Earthworks approx.	256 000	m^3
Containment barrier cost per m^2	R 353	
Cover costs	R 120	
P&G and fees, land, access and drainage	50%	
Capex costs	R 30 397 960	
Cost per m^3 of space	**R 148.43**	

7.2 Irrigation

One of the beneficial disposal methods for sludge is surface irrigation. This practice has for example been used in North America for some time for disposing of wastewater treatment plant sludge in plantations. Powerful pumps are used which are able to broadcast the sludge from tankers for many metres either side of access roads through the plantations. Another option is the irrigation of turf, which is then sold commercially. Sludge from the Darvill sewage works in Pietermaritzburg is disposed of in this manner. In order for this method to be used the sludge must be substantially pathogen free. It would certainly not be possible to irrigate sludge derived from on-site sanitation such pit latrines due to the high solid waste fraction. If the disposal site is close to the works, this will be a very economical disposal option. If road tankers have to be used it will be less so depending on the distance travelled.

7.3 Composting

Johannesburg Water has produced two publications entitled, *Sewage sludge solar drying and composting* and *Sewage sludge composting*, which give detailed instructions on drying and composting of sewage sludge. Composting with sludge involves use of a sludge cake in conjunction with a carbon supplement such as wood chips. Three composting systems are most commonly used, namely:

- an aerated static pile.
- a mechanically turned windrow.
- a vessel.

Johannesburg uses the mechanically turned windrow system, due to the ease of operation relative to the other two options. The mix that is used in the case of Johannesburg Water is:

- Dewatered sludge (total solids concentration between 18 % and 20 %).
- Recycled woodchip (16 mm to 200 mm) for stability and the provision of air voids.
- Fresh bulking agent (up to 200 mm) including fine material (sawdust, leaves, etc.) for the enhancement of the Carbon/Nitrogen (C/N) ratio.
- Recycled, unscreened composted material to increase the dry solids concentration of the initial compost mix. The recycle ratio is limited to 10 % of the volume of the new compost mix.

In Johannesburg, the ratio of total bulking agent to sludge cake by volume varies between 2:1 and 3:1, unless the moisture content of the sludge has a total solids concentration lower than 16 %, in which case it will be 1:1. The aim is to keep the moisture content around 50 % during the composting process.

Essentially, the aim is to achieve an optimum C/N ratio of somewhere between 25 and 40:1. Any lower than 20:1 and nitrogen is lost from the process through the stripping of ammonia to the atmosphere and any higher than 40:1 and the process becomes too slow. In Johannesburg, the dimensions of the windrow are 5.5 m wide and 1.5 m high.

Residual oxygen levels should be maintained between 5 and 15 % during the composting period because low oxygen levels inhibit the process and excessive oxygen levels cool the windrows down. In practice, oxygen levels are difficult to control and oxygen input is determined by temperature in the windrow. Windrows are not turned for the first two days and after that they are turned every second or third day until composting is complete (usually 21 to 30 days depending on temperatures). The frequency or turning is determined by the average temperature in the windrows.

The most efficient composting occurs in the temperature range of 35 % to 55 % and is inhibited when temperatures exceed 65^{o} C.

In Johannesburg, after composting, the windrows are sieved through a screen aperture of 16 mm to remove oversize woodchips. The windrows are then cured for between 60 and 90 days, with the moisture content maintained between 40 % and 50 % and it is during this period that the temperatures are allowed to reach the higher temperature of about 65^{o} C for five consecutive days to kill pathogens and seeds (including *Ascaris* ova). Depending on the use of the final product, after the curing, the compost may be screened down to a minimum of 10 mm.

In Johannesburg, they have found that one dry ton of sludge produces between 2 and 3 m^3 of compost, depending on the screening aperture used and the moisture content.

If Wastewater Treatment Works sludge is channelled to a composting facility and it amounts to less than 10 tons per day, then no EIA process needs to be undertaken. This is on the understanding that the WWTW sludge is no longer classified a hazardous waste. On the other hand, if sludge from pit latrines (which is still classified a hazardous waste) is to be similarly processed, then the threshold would be less than 500 kg per day.

Costs reported for turning sewage sludge into compost are in the order of R500 per m^3.

7.4 Latrine Bio-solids Dehydration and Pasteurisation (LaDePa)

The Latrine Bio-solids Dehydration and Pasteurisation (LaDePa)process was developed by eThekwini Water and Sanitation (EWS) in partnership with Particle Separation Solutions (Pty) Ltd (PSS) and piloted over the period 2009 to 2012. In response to thousands of on-site sanitation facilities with full pits across the municipality, EWS initiated a pit-emptying programme, with the service offered free to households once every five years. The volume of sludge requiring disposal is approximately 7000 m^3 per year. 35,000 VIP latrines were emptied during first phase of this project with around 70% of the sludge produced buried on-site (where sufficient space existed). In the more densely-populated areas, sludge had to be transported off-site and processed elsewhere. The LaDePa process was developed as possible means of processing this sludge, reducing the quantity of solids that had to be sent to sanitary landfill and potentially creating a product with a market value.

Figure 7.4 illustrates the stages of the LaDePa process. Sludge removed from pit latrines consists of faecal sludge together with solid waste, including material used for anal cleansing (e.g. toilet paper, newspaper, plastic packaging) and other refuse (e.g. clothing, hair extensions, disposable nappies, sanitary pads, rope, bottles and cans). The LaDePa process separates the faecal sludge from the solid trash material by compressing the mixture in a screw compactor with lateral ports, through which the faecal sludge is extruded (Stage 1). The trash material exits from the end of the screw conveyer.

The sludge is deposited in a 25 to 40 mm thick layer of extruded cylinders (of 6 mm diameter) onto a porous moving steel belt. Hot exhaust gases from the plant's internal combustion engine pass upwards through the belt to pre-dry the sludge (Stage 2). The sludge is then further dried and pasteurised with medium wave infrared radiation (MWIR) under vacuum (Stage 3). The residence time of the sludge on the belt is 8 minutes (4 minutes subject to upward exhaust gas flow at 500 °C and 4 minutes under MWIR under vacuum at 750 °C) (Harrison & Wilson 2012).

A sterilised[2], pelletised product is produced with a typical solids content of 60% (dependent on the feed moisture content). The pellets contain organic matter, nitrogen (N), phosphorus (P), potassium (K) and micro-nutrients critical to plant growth.

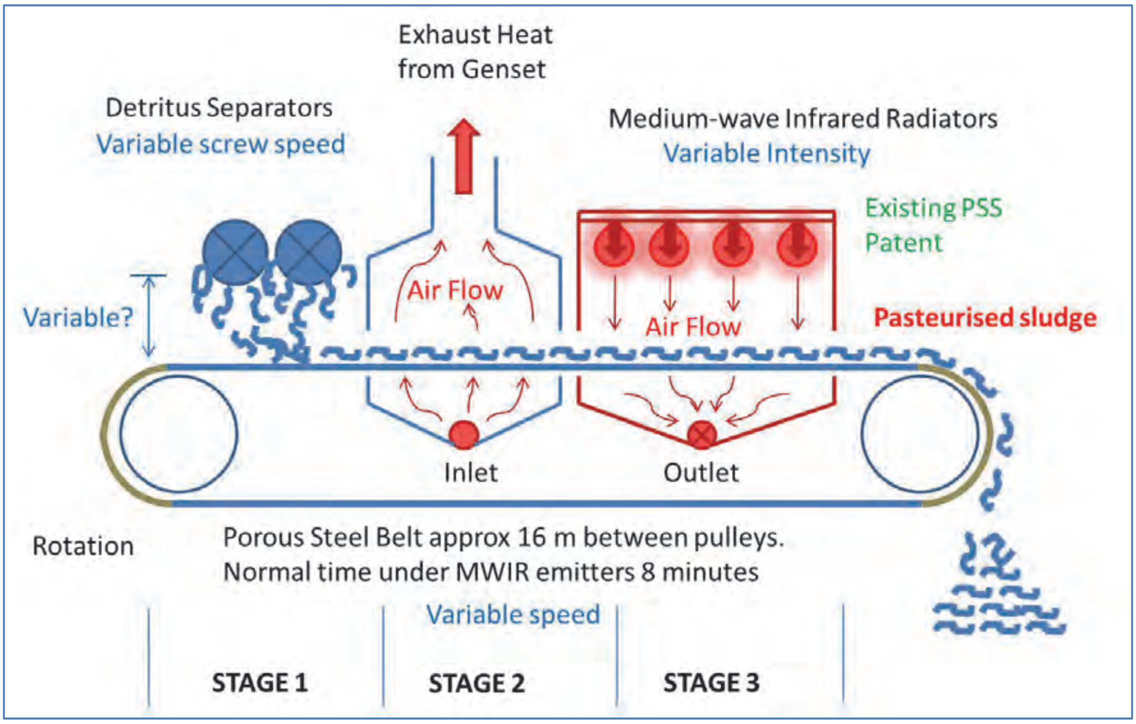

Figure 7.4 Schematic of the Ladepa Process (from Cottingham, 2013)

[2] Given the design of the process it is to be expected that the pellets will be fully pasteurised. However, there is a possibility that *Ascaris* ova located near the centre of the 6 mm diameter pellets may not be exposed to enough heat to be killed. In 2014/15 eThekwini and UKZN plan to carry out scientific trials to determine the operational parameters which will guarantee a safe product.

Initial analysis of pellets produced from the process indicate lower levels of N, P, K and micro-nutrients than commercially-available organic fertilizers, but still of levels to be of benefit in land application (Plant Laboratory Analytical Services, KwaZulu-Natal Department of Agriculture 2011)[3].

Figure 7.5 A view of the second and third stages of eThekwini's pilot LaDePa machine

An economic analysis on the LaDePa process carried out by the UKZN's Pollution Research Group in 2013 (Cottingham et al., 2013) indicated that the cost of turning a cubic metre of pit latrine sludge into pellets was in the order of R2 000, excluding the emptying and transport costs. Offsetting this cost is the fertilizer value of the pellets, which can be estimated at approximately R400 per cubic metre of pit sludge. However, after factoring in transport and spreading costs, which are high relative to the transport and spreading costs of a comparable inorganic fertilizer, it was found that the pellets would not have any commercial value. This is not to say they would have no value, as they can be used by the city as a low grade organic fertilizer for the parks, verges and community gardens. There is also the possibility that micro-nutrients (Zinc, Calcium, etc.) present in the sludge will prove to be of significant value. Trials are ongoing.

7.5 Black Soldier Fly

The harnessing of the larvae of the black soldier fly (*Hermetia illucens*) for the processing of faecal sludge is a relatively new concept in sanitation engineering. The black soldier fly, of the family Stratiomyidae, is a common and widespread fly, whose larvae are common detritivores in compost heaps (Wikipedia, 2014). However, unlike other flies the adult (winged) black soldier fly has no

[3] Note that the sludge processed for the pellets that were analysed had been stored for several years after removal from the pit, therefore significant nitrogen loss might have taken place. Systematic sampling of several batches of pellets will be required to determine useful values for average nutrient content.

mouth parts and only lives long enough to reproduce. In its larval stage it feeds on any rotting organic matter, which includes faeces if it is available.

Figure 7.6 Larvae of *Hermetia illucens*, the black soldier fly (Wikipedia)

Figure 7.7 An adult black soldier fly laying eggs in cardboard. The adult fly poses no health risk, having no mouth parts and living only long enough to reproduce (Wikipedia)

Black soldier fly larvae, termed BSFL, are kept in compartments where they are fed a diet of whatever organic waste must be disposed of. When they are ready to exit the larval stage they void their digestive tracts and lose their mouth parts, which are replaced with parts designed for climbing. A ramp is provided and the intermediate stage prepupae climb this ramp, at the top of which they can be easily harvested. The pupae are high in protein and fat and therefore make a high value animal feed. The larval waste products have value as a soil conditioner.

The eThekwini Metropolitan Municipality is currently in discussions with the company Biocycle, a subsidiary of the company Agriprotein, to construct a 40 ton per day BSF plant at one of its wastewater treatment sites in Durban. Provisionally this plant would process a 50/50 mix of food waste and waste emptied from the city's many urine diversion toilets and pit latrines. The city would undertake to provide the latter and Biocycle will build and operate the plant. Preliminary financial analysis of this proposed BSF site indicates that it can pay for itself within five years without any charge for accepting the waste. Questions that must be answered are whether the BSFL will be as productive and efficient feeding on faecal waste which is already substantially digested (i.e. which is not fresh), and whether the end products will be free, or can be made to be free, of pathogens.

7.6 Stabilisation with quicklime

Another method used for the stabilisation and disposal of sewage sludge is mixing with quicklime (Calcium Oxide, CaO). Quicklime is made by heating limestone ($CaCO_3$), a relatively abundant rock best known as the raw material for the production of cement. The market price of quicklime is similar to that of cement.

Adding quicklime to sludge both generates heat (as the CaO reacts with water in an exothermic reaction to form hydrated (or slaked) lime $Ca(OH)_2$) and raises the pH of the sludge. With enough quicklime (typically 20% to 40% by mass) and enough mixing the temperature can be raised high enough for long enough to kill pathogens, while the pH is raised above 12. In agriculture slaked lime is regularly used to raise soil pH, so the nutrient-rich lime-enhanced product of sludge stabilization by lime addition is a useful product.

The costs of sludge stabilisation by mixing with quicklime can be expected to be similar to the costs of composting.

8. CONCLUSIONS

This report set out to answer the following questions:

- Has this method of sludge disposal been tried before?
- What is the fate of pathogens which are buried in the ground?
- How does sludge change after it is buried in the ground?
- What is the fate of the nutrients in the sludge after it is buried in the ground?
- How should one go about burying sludge in the ground and what will this cost?
- Can one make use of the nutrients in the buried sludge, and what might such use be worth?
- What are the alternatives to this method of sludge disposal, and what do such methods cost?
- If one wishes to use this method for sludge disposal, how should one go about acquiring authorisation from the relevant authorities?

Taking them in turn, the following can be concluded:

Has this method of sludge disposal been tried before?

Entrenchment as a disposal method for wastewater treatment works sludge was pioneered in Maryland, United States in the mid-70s and has been the subject of extensive research since that time. The Maryland research, later extended to Philadelphia, indicates that entrenchment is a safe method for sludge disposal. Repeated trials over more than 20 years have not detected a significant impact on the groundwater, despite very heavy application rates (up to 660 dry tons per hectare). Trials with fast growing poplar trees indicate that tree growth is significantly enhanced when these trees are planted in close proximity to the entrenched sludge.

What is the fate of pathogens which are buried in the ground?

The ovum of *Ascaris lumbricoides* (roundworm) is considered to be the hardiest of pathogens in faecal sludge and is therefore used as a marker organism for determining the degree to which sludge can be considered safe to handle. *Ascaris* is rife in Durban and sludge removed from pit latrines typically has average egg counts of several hundred ova per gram of sludge. The presence of *Ascaris* has been monitored in buried sludge over a period of 48 months and these results show a complete die off over a period of three to four years. It can therefore be reasonably concluded that, assuming there was any reason to do it, buried sludge can be safely dug up after 4 years. Tests for the presence of *Ascaris* on surface soil samples after 48 months indicated no significant difference between the soil in the entrenchment area and background soil samples from a similar area where no sludge had been handled.

How does sludge change after it is buried in the ground?

Over time sludge buried in the soil dewaters and decomposes. After several years it is difficult to distinguish from the surrounding soil. Over the course of four years the pit sludge buried at Umlazi changed as follows:

- The median COD decreased from 0.25 g COD/g dry sample to 0.05 g COD/g dry sample

- The median volatile solids decreased from 60% to 3%
- The moisture content reduced from 75% to 13%

These data indicate that the organic matter has largely decomposed over the four year period.

What is the fate of the nutrients in the sludge after it is buried in the ground?

High concentrations of nitrogen and phosphate have been observed in the leachate in the immediate proximity to the sludge, and occasional spikes of high nitrate and phosphate have been observed in the subsurface flow at drainage lines below the Sappi site, which has a fairly shallow soil over a shale layer with low permeability. However no significant increases in nitrate or phosphate have been detected over the monitoring period in any of the boreholes located between the sludge entrenchment sites and the nearest downslope streams. After three years the phosphorus and potassium levels in the soil immediately around the sludge are raised, but within less than a metre are no different to background levels. After three years there is no significant difference between the nitrogen levels in the sludge, in the soil around the sludge and in the background soil. A set of very well controlled leachate monitoring trials on different soils on sloping ground (which are ongoing) show that after four months less than 0.2% of the nitrogen has leached out of the sludge, and less than 0.004% of the phosphorus has leached. While some of the N and P has been taken up in the trees this will only account for a small percentage of the nutrient loading. It is probable that much of the P has bonded with clay particles in the soil in the immediate vicinity of the sludge and has not moved far, while it is probable that much of the excess N introduced to the soil has been recycled back to the atmosphere by nitrifying and denitrifying bacteria. Further work is required to better understand these natural processes.

How should one go about burying sludge in the ground and what will this cost?

The Maryland, United States sludge entrenchment work which inspired this research is based on maximizing disposal as opposed to maximising nutrient uptake/beneficiation. While the Umlazi and Sappi trials described here have not detected any negative environmental effects, it would make sense to apply smaller amounts of sludge more often if one is to maximize the nutrient uptake in the crops which are intended to benefit from the process. However, that said, it would be inefficient and expensive to bury very small amounts of sludge.

Sludge entrenchment lends itself to labour intensive methods, which maximize employment. The sludge should be transported in sealed drums to prevent spillage and wastage. These drums should be sized appropriately for labour intensive loading, offloading and haulage methods (i.e. not more than say 70 litres of sludge per drum). Trenches should be dug no more than a spade width (300 mm) and 400 mm in depth. These trenches should be filled with sludge to a depth of 300 mm and then backfilled. The surplus soil should be mounded over the trench as the sludge will reduce approximately 50% in volume as it dewaters and decomposes. If trenches of these dimensions are dug between all rows in a plantation (assuming a spacing between rows of 3 metres) the total amount of sludge buried will amount to approximately 140 dry tons/hectare.

The cost of sludge entrenchment can be expected to cost approximately R60 000 per hectare assuming an entrenchment rate of 300 m^3 of wet sludge per hectare and a haulage distance of 30 km, i.e. R200/m^3. At approximately R3.20/m^3.km transport quickly becomes the dominant factor in the cost calculation. Further costs will be incurred establishing leachate and groundwater monitoring well points, which might amount to several hundred thousand Rands. A monitoring establishment cost of R10 000 per hectare is a reasonable budget figure (assuming that one monitoring well will cover at least 10 hectares).

Other methods of sludge disposal, for example using landfills, incineration, pelletizing and composting can be considerably more expensive.

Can one make use of the nutrients in the buried sludge, and what might such use be worth?

In the trials conducted as part of this research the results indicate that timber tonnage will increase by up to 50% for plots with sludge entrenchment relative to those using conventional methods of fertilisation. Over a 10 year growing cycle this would translate into increased revenue of R25 000 at current prices. This is less than the cost of entrenching the sludge, but it does nevertheless offset the cost of the sludge disposal.

What are the alternatives to this method of sludge disposal, and what do such methods cost?

Municipalities in South Africa are used to dealing with wastewater treatment works sludge disposal. Very few, however, have to date tackled the disposal of pit latrine sludge at any scale, with eThekwini being the only notable exception.

Wastewater Treatment works sludges are generally disposed of in landfills, or they are composted. In some cases they are irrigated or surface spread after stabilisation using anaerobic digestion or lime addition. Landfill and composting are fairly expensive processes, with costs in the order of R500 m^3 being reported.

If one wishes to use this method for sludge disposal, how should one go about acquiring authorisation from the relevant authorities?

Unless one is dealing with small volumes of sludge (literally the contents of just a few pit latrines) which is being disposed of on or near the site where it originated, then an Environmental Impact Assessment (EIA) will have to be undertaken in order for sludge entrenchment to be used at any scale worth the effort. The EIA must be done by an independent professional and will involve stakeholder consultation, specialist studies and the review of alternatives, risks and benefits. This process is lengthy and expensive (for example, a one to two year process costing anywhere from R100 000 to R500 000 is not unlikely). It would therefore make sense to acquire authorisation for a large scale, long term DRE programme where one EIA can cover all that will be required for, say, a 10 year planning horizon.

Summary

No other method of sludge disposal is more economical than simply burying it in the ground, especially if the burial site is close by the site where the sludge is collected. In the ground, sludge decomposes by natural biological processes and after a few years is barely distinguishable from the surrounding soil. After three years even the hardiest pathogens such as *Ascaris* die off. Despite high loading rates no significant impact on groundwater has been observed in the trials to date over four years of monitoring, and there is evidence that the phosphorus and potassium in the sludge binds to soil particles near the point of burial while the nitrogen returns to the atmosphere.

When sludge is buried in close proximity to eucalyptus trees, which form a major part of the South African forestry plantations, growth is enhanced by up to 50% in terms of total timber volume, although after only four years it is too soon to say if the magnitude of this difference will be sustained over a nine or ten year growth cycle. This additional timber volume will offset the cost of the entrenchment process by as much as a third or even a half. The increased potassium and phosphorus levels in the soil will be lasting and will benefit future tree growth cycles.

9. RECOMMENDATIONS

Sludge entrenchment provides a practical and beneficial technique to deal with the problem of disposal of potentially dangerous faecal sludge from pit latrines and wastewater treatment works. Unfortunately it is still too little known or understood in South Africa and it is improbable that permission will easily be obtained to adopt this method at scale.

It would be advisable to continue with the monitoring of the experimental plot at Sappi's Shafton plantation to see whether the enhanced growth in the plots with sludge is fully sustained to the end of the ten year growth cycle, i.e. to December 2019, and it would be particularly interesting to see if the subsequent growth cycle was enhanced by the potassium and phosphorus which has been added to the soil (the nitrogen having returned to the atmosphere). This work would not require a significant research budget, as all that would have to be done would be to measure the trees once per year and to sample the boreholes perhaps twice per year.

Meanwhile it is quite possible that other methods of sludge burial might yield better results compared with these trials. For example smaller amounts of sludge could be buried but with a greater frequency – say once every three years in the same location. It is recommended that trials are conducted comparing different entrenchment methods to see which gives the best return on investment.

These trials have been carried out with agroforestry in mind. It is not recommended that sludge is used as a fertilizer or soil conditioner in close proximity to food crops such as vegetables. However South Africa and in particular KwaZulu-Natal has a large sugar cane industry, and it is recommended that trials be conducted with sugar cane instead of eucalyptus trees as the associated crop. Entrenchment in a cane field would be significantly easier than entrenchment in a forestry plantation, due to the absence of roots and stumps.

Finally, more work must be done to fully understand the fate of the nitrogen and phosphorus in the buried sludge. On the strength of the evidence in this study, only a very small fraction (less than 1%) of these elements leach out of buried sludge. This implies that a significant fraction of the remainder either stays where it is (adsorbed to the soil, in the case of phosphorus and potassium) or returns to the atmosphere (in the case of nitrogen). More long term work is required to prove these hypotheses.

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APPENDIX A

Guidelines for the Entrenchment of Pit Latrine and Wastewater Sludge

GUIDELINES FOR MUNICIPAL ENTRENCHMENT OF PIT LATRINE AND WASTEWATER SLUDGE

While further research of the benefits and risks associated with deep row entrenchment is warranted to better understand the interaction of entrenched sludge with the environment and with the species of tree or other crop it has been entrenched to benefit, municipalities can begin to implement this method with proper management and monitoring.

The South African *Guidelines for the Utilisation and Disposal of Wastewater Sludge* provide a matrix for the development of new options for wastewater sludge management; however, deep row entrenchment is not addressed specifically. In addition, the existing guidelines have been developed exclusively for sludge which has been treated at a wastewater treatment works (WWTW) and the implications for VIP sludge are not addressed. While two of the applications addressed in these guidelines can be used for either VIP sludge or WWTW sludge, it is important to keep in mind that separate analyses of these different sludges should be made before application as they differ in several key respects:

- While VIP sludge can be expected to have a low pollutant content because it originates exclusively from domestic sources,[4] it is less stable than WWTW sludge and water soluble elements have not yet been removed, with the result that greater movement of pollutants through the soil and water table might be seen[5].
- Because WWTW sludge originates from multiple domestic, commercial and industrial sources where pollutant disposal may fluctuate widely over time and from one treatment works to another, the pollutant level of WWTW sludge can never be assumed and must always be assessed, along with the receiving soil, before application, to ensure that the combined loading of pollutants at the entrenchment site will not pose a threat to the environment.
- While processes at the WWTW may have reduced the presence of pathogens in WWTW sludge significantly, both WWTW sludge and VIP sludge can be assumed to have viable pathogens and should be treated as hazardous materials. However, because the odour of WWTW sludge has been reduced significantly through stabilisation, it will not attract vectors to the extent that VIP sludge would. In addition, as the smell of WWTW sludge is less offensive it can be applied at closer proximity to settlements than VIP sludge without creating a nuisance. Sludge from pits which have not been disturbed for some time may also have stabilised to the point that it has no odour.

[4] This assumption could, however be questioned on the basis that the pit often has to accommodate the solid waste of the household if solid waste collection is not provided, and waste associated with home businesses, could potentially contain significant pollutants.
[5] Heidi Snyman, pers. comm.

Volume 4 of the *Guidelines* addresses two types of applications of wastewater sludge at higher than agronomic rates: once-off application of less than three times in a five year period, or continuous sludge application, a method which requires less stringent planning and monitoring, which is more than three times in a five year period. With deep row entrenchment, sludge is normally applied on a crop planting/harvest cycle which is typically longer than five years, and thus could be categorised as "once-off" application. However, entrenching sludge in deep rows allows sludge to be applied at much higher rates, making it necessary to consider some of the implications addressed in the guidelines for "continuous sludge application."

The guidelines presented in this chapter are intended to provide a practical framework for entrenchment of both wastewater and pit latrine sludge which adequately protects the environment and public health while avoiding excessive measures which could prove prohibitive to the implementation of this method both in terms of costs and time. Volume 4 of the *Guidelines* forms the basis of many of the recommendations, in addition to the experience gained with entrenchment in the trials conducted in this study as well as earlier trials conducted abroad. While these recommendations may prove over time to be overly conservative, they are intended to ensure that all variables are considered. As more experience is gained with this disposal method in practice, it is expected that these guidelines will continue to be revised until they reflect a solid understanding of the interactions between entrenched sludge and the surrounding environment.

The following guidelines provide options for municipal application of the deep row entrenchment method for both VIP sludge and treatment works sludge:

- *Commercial entrenchment (pit latrine sludge or treatment works sludge)*

This would involve a larger scale partnership between a municipal wastewater treatment works and a forestry company in which the sludge generated within a municipality is transferred to a forestry company through some mutually beneficial arrangement. Alternatively, the municipality might contract a forestry company to manage a timber crop on entrenched sludge on municipal land.

- *Municipal decentralised entrenchment (pit latrine sludge or treatment works sludge)*

This option involves entrenchment of sludge on relatively small tracts of municipal land, particularly in rural areas where utilising sludge close to its point of origin on smaller plots represents a significant savings over transporting sludge long distances for more centralised use/disposal. Trees or other non-edible crops would be grown on the sludge.

- *Municipal burial sludge on household premises (pit latrine sludge)*

This option provides recommendations for situations where there is space at the site where a pit is emptied for the sludge to be entrenched on site. The entrenchment of the sludge provides a protective barrier over the pathogens, and the planting of trees provides a means to derive some benefit from the nutrients in the sludge.

1. Commercial deep row entrenchment for forestry

Both VIP and WWTW secondary sludge can be entrenched within an existing forestry site, reducing the costs and problems associated with other disposal options and yielding an economic benefit in terms of greater biomass of timber produced. While fruit trees and food crops with edible parts grown above the soil could benefit from the nutrient supply provided by entrenched sludge, the possibility of the covering layer of soil being disturbed by heavy rains or activities and thereby exposing pathogens in the sludge makes it an inappropriate option for commercial production of food. Class ***A*** sludge which has been treated to destroy pathogens may however be used to grow food commercially either through surface application, shallow incorporation or deep row application.

1.1 Legal requirements

The sludge producer and sludge user must have a legal agreement/contract if the sludge is utilised by a third party. [6] Formal application must be made to the competent authority for authorisation of the proposed activity at the proposed site. Details for this process can be found in the Environmental Impact Assessment Regulations (GN No. R. 660 of 30 July 2010). The applicant must appoint an Environmental Assessment Practitioner (EAP) to prepare the necessary basic assessment, scoping report or EIA, including handling the public participation process required for obtaining authorisation. A rejected application can be appealed; in addition, it is possible to apply for exemption from the process.

The costs and benefits to stakeholders in the local community must be assessed prior to commencing the activity, in addition to needs and rights. If an environmental impact assessment is required a public participation process must be undertaken.

Once the applicable permits and authorisations have been granted, management and monitoring of the entrenchment site becomes self-regulatory. DWA will provide a list of the records that must be kept by the sludge producer and disposal site owner/operator.

1.2 Financial viability

In order to determine whether deep row entrenchment of sludge for commercial forestry is a viable option for a municipality, a cost benefit analysis should be conducted to determine:

- The current expenditure by the municipality sludge disposal versus anticipated expenditure for disposal of sludge by entrenchment. Can expenses be reduced by simplifying or bypassing some stages of treatment at the works which are not essential for sludge destined for entrenchment? The costs of testing sludge for pollutant levels before disposal must be added in.

[6] The conditions which must be included are provided in the Guidelines for the utilisation and disposal of wastewater sludge, Volume 4, Appendix 3.

- The current expenditure on transport to the disposal site versus anticipated expenditure for transport to a deep row entrenchment site (including worker and public safety measures and measures to address contamination of vehicles if sludge is currently not transported off site)
- Income, if any, generated by existing disposal alternatives versus anticipated income generated by deep row entrenchment
- Period for which this cost benefit analysis can be expected to apply: Can the designated forestry site accommodate all the sludge generated at the works or will it reach capacity after a certain number of years? How often can sludge be entrenched or will it be stockpiled at the works during the growing cycle?

Similarly, a cost benefit analysis should be conducted by the forestry company to determine:

- Increased / decreased costs of obtaining, developing and operating a site for deep row entrenchment due to more stringent environmental impacts (limitations on site selection, preparation of trenches, entrenchment equipment, monitoring, savings on fertiliser, protective equipment and training for personnel)
- Cost of desired quantity of sludge purchased from municipality
- Anticipated increased savings/profits resulting from entrenchment (increased biomass production)

If the sludge is to be used for the rehabilitation of mine spoils or restoration of habitat, a similar cost benefit analysis can be conducted to determine the viability of deep row entrenchment in contrast with alternatives.

1.3 Site characterisation and selection

A site with any of the following characteristics should not be considered for deep row entrenchment unless mitigation measures can be taken to alleviate any potentially negative impacts:

- Within the 1 in 100 year flood line (wetlands, vleis, pans and flood plains) due to risk of water pollution.
- Unstable areas (fault zones, seismic zones and dolomitic or karst areas)
- Steep gradients(greater than 15 degree) due to potential for instability and erosion, and greater movement of pollutants
- Distance to fissured rock below surface less than 3m
- Areas of groundwater recharges
- Highly permeable soils
- Areas immediately upwind of a settled area
- Natural habitat of endangered species which could be disturbed by entrenchment activity

If the site is to be surveyed for the first time, the following characterisations should be completed in order to assess whether the site is suitable and, if it is, to establish baseline data to be used to assess the impact of entrenchment on the environment over time. Characterisations should be submitted as expert reports with the EIA application:

- **Topography and hydrogeology:** Location and depth of hard, impervious layers and permanent and perched water tables should be characterised. The direction and flow of underground waters and potential for underwater drainage should be assessed.

- **Soil:** The surface and subsoil soils should be assessed in terms of structure, permeability and cation exchange capacity (CEC) to indicate the extent to which the soil will retain contaminants and minimise leaching into the surrounding area. Soils should have a clay content of at least 20% and a pH of above 6.5 to limit mobility of metals. Lime can be added to the soil to raise the pH. A baseline analysis of the nutrients, trace elements and metals present in the soil should be conducted in order to assess the impact of sludge on native soil over time.

The Department of Water Affairs provide two systems of assessing the metal content in the receiving soil depending on the use of sludge. In cases where sites with limited public access are used to cultivate industrial crops (e.g. timber), maximum permissible levels (MPL) are provided for metal concentrations for the receiving soil. For more details refer to Section 9.1.7.1. This system is designed for wastewater sludge. As VIP sludge comes from domestic sources it is not expected to contain harmful levels of metals.

- **Surface water:** Possible surface water resources should be identified and sampled to determine baseline values which can be used for comparative purposes should surface contamination occur during sludge entrenchment.
- **Groundwater:** The aquifer must be classified in terms of yield, depth, and strategic value. A buffer of 200m should be maintained from surface water, boreholes and the recharge zone of major aquifers, sole-source aquifers or other strategic aquifers. The hydraulic gradient should be determined to assess the position of the monitoring boreholes. Groundwater quality (up gradient and down gradient) should be assessed to establish baseline values for monitoring.
- **Site stability assessment:** An engineering assessment must be completed in order to inform the spacing and orientation of trenches. As a precautionary principle the shear strength of sludge should be assumed to be zero. Trenches should be dug parallel to the ground contours rather than parallel to the slope direction.

1.4 Characterisation of sludge

An initial characterisation of both the soil and sludge can provide information to optimise application rates and economic gain. These include:

- Physical characteristics: pH, total solids (TS), volatile suspended solids (VSS), volatile fatty acids (VFA)
- Nutrients: Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP) and potassium
- Metals and micro-elements
- Organic pollutants

Testing of sludge to determine pollutant loads must be done any time there is reason to believe there has been a change in the sludge stream at the wastewater treatment works or if there is reason to believe pollutants have been disposed of in a pit. Unless sludge has undergone special treatment to kill pathogens, it can be assumed that it poses a risk for disease transmission and safety measures should be followed for transport, handling and burial.

While there are some restrictions on the use of microbiological class[7] ***B*** or ***C*** sludge or pollutant class ***b*** or ***c*** sludge for the growing of crops to be eaten by humans or livestock, there are no restrictions on any of the categories for industrial crops with the exception of restricting public access where sludge with microbiological class ***B*** or ***C*** is applied to the surface. As proper burial overcomes the risk of human contact, deep row entrenchment can be considered for all sludge classes.

1.5 Designing and preparing the site

The site should be designed and prepared to allow adequate access for heavy trucks and field equipment in all weather conditions.

Trenches should be dug parallel to the contours of the slope. Trench spacing and dimensions will depend to some degree on the results of the soil stability assessment and depth to the water table. Enough space must be left to accommodate the vehicle which is delivering the sludge and the backfill heaped beside the trench without the trench collapsing. It is advisable to prepare test trenches to ensure that the desired dimensions and spacing of trenches are feasible for the specific site conditions.

In terms of the impact on degradation of entrenched sludge over time, optimal dimensions for trenches are 800mm deep and 600mm wide. The spacing between rows should be determined by standard practice for the intended tree species but should also take into consideration soil stability, with adequate space to accommodate the vehicles digging the trenches and delivering the sludge. Assuming a row spacing of 3m between the centres of trenches 800mm deep and 600mm wide, this will allow for an application rate of 990m^3 of sludge per hectare of plantation, allowing a covering of 300mm of soil over the entrenched sludge.

The backfill soil should be heaped over the trench to allow settling and to prevent erosion. Monitoring boreholes should be located to intersect groundwater moving away from a disposal site.

1.6 Handling of sludge

Due to the likelihood of viable pathogens in sludge it should be handled as a hazardous waste (containing infectious substances) during transportation. Transporters must be informed of the nature and risks of the load and carry accurate documentation. Hazchem placards should be fitted to the vehicles. All road accidents must be reported to the Department of Transport Local

[7] See Introduction for sludge classification system

Authorities, the Competent Authority and the Department of Water Affairs and steps must be taken to minimize the impact of any contamination on public health and the environment.

1.6.1 Storage

Storage of sludge at the disposal site is not recommended because of the issues of odour, vector attraction and potential contamination of the site surface or leachate. Sludge should ideally be delivered directly to the trench and covered with soil the same day. If storage of WWTW sludge on site cannot be avoided, it should be stored in a specially prepared pit to avoid surface contamination and covered securely so that it cannot be accessed by animals or other vectors. If sludge is stored in an area for more than 90 days then the area is considered a disposal area and a disposal permit is required. VIP sludge should not be stored on site because of its higher vector attraction factor.

1.6.2 Preventing transmission of pathogens

It is recommended that municipalities provide regular (3 monthly) deworming treatment to workers working with sludge and provide a full orientation to educate workers about pathogens, routes of transmission and procedures to protect their health before they begin work. Workers must wear protective gear while handling sludge to prevent infection by bacteria, viruses or intestinal parasites in the sludge. Eggs can become airborne when sludge is handled and so it is important that workers wear masks, gloves, boots and overalls when handling sludge. It is also critical that rigorous protocol be established to avoid transfer of pathogens to surfaces by wearing contaminated gloves, boots or clothing out of the site or when driving vehicles and to ensure that vehicle wheels do not become contaminated, carrying pathogens with them when they leave the site. It is also important that workers are provided with the means to disinfect their clothing so that contaminated clothing is not taken to their homes, increasing the likelihood of infection of their family members. Facilities should be provided at the site for workers to shower and disinfect their hands as needed during and at the end of their work day.

1.7 Application of sludge

1.7.1 Application rate

While the Department of Water Affairs recommends an application rate limit of 120 tonnes dry sludge/ha/year for surface and shallow incorporation of sludge, it also provides a formula for calculating a permissible application rate (PAR) which can be used to demonstrate that higher application rates can be safe for a particular soil without negatively impacting the environment. The authorising authority may approve a higher application rate based on the particular characteristics of the site in terms of soil properties, depth to aquifer, type of aquifer, distance from surface water resource, and other characteristics. Entrenching sludge for forestry allows for far higher loading rates than would be possible on the surface and also moderates the impact of metals in a number of ways different to other utilisation options:

- While high loading rates for surface application of sludge for agriculture would dramatically increase the presence of pollutants in run-off, entrenched sludge at any loading rate should have no contact with surface water if application was completed without contaminating the soil surface.

- While surface application of sludge results in highly aerobic conditions, under which nitrification occurs rapidly and metals mobilise more quickly through the soil profile, entrenchment results in anaerobic conditions, resulting in slow release of pollutants from the sludge as tree roots introduce oxygen into the sludge over the course of several years.
- While landfill disposal creates conditions where sludge is entrenched and nutrients and pollutants have no means to move except through the soil profile, deep row entrenchment involves the planting of trees which take up nutrients, leachate and metals, minimising the movement of these out of the trench. While uptake of high levels of metals in edible crops could represent a health risk, uptake by industrial crops represents no health risks.

While surface application is usually done yearly or more frequently, once-off application of high loading rates can be used with entrenchment to match the growing cycle of the crop. This also minimises human contact with sludge as application is both far less frequent and, once applied, the covering soil provides a barrier between the sludge and workers.

Data from sites used for entrenchment in the US for nearly 30 years and sites currently in use in South Africa over 3 years indicate that application rates of 360 to 800 tonnes dry sludge/ha/year provide maximum benefit to trees and have not negatively impacted the environment. However, ideal loading rates and risk to the environment will vary depending on tree species, pollutant levels in receiving soil and sludge, and site factors such as soil permeability.

The permissible application rate (PAR) can be calculated as follows:[8]

$$\mathrm{PAR} = \frac{\mathrm{MPL} - \mathrm{Soil_{conc}}}{\mathrm{Sludge_{conc}}} * 3900$$

Where:

PAR	= permissible application rate (tonne/ha)
MPL	= maximum permissible level (mg/kg) (See Table 1)
$Soil_{conc}$	= the actual metal content of the soil (mg/kg)
$Sludge_{conc}$	= metal concentration in the sludge that will be applied (mg/kg)
3900	= conversion factor to account for soil density (1.3 t/m^3) and sludge incorporation depth of 300 mm

[8] Guidelines Vol. 4 p. 22

Table 1 Maximum levels of elements allowed in sludge to be applied at high loading rates

Elements	Maximum Permissible Level (MPL) mg/kg
Arsenic (As)	20
Cadmium (Cd)	5
Chromium (Cr)	450
Copper (Cu)	375
Lead (Pb)	150
Mercury (Hg)	9
Nickel (Ni)	200
Zinc (Zn)	700

As discussed previously, these guidelines were put in place for management of wastewater sludge and are not designed for pit sludge, which may be less stable and more variable in terms of potentially harmful components. However, as pit sludge originates from domestic sources, it is not expected to contain high levels of pollutants. In the absence of parameters set specifically for pit sludge, the wastewater guidelines can provide a measure of safety in the entrenchment of pit sludge.

1.7.2 Application method

Sludge should be delivered directly to trenches to prevent surface contamination and contamination of vehicles which may drive over sludge deposited at the side of trenches. Trenches should be backfilled the same day with a minimum of 300 mm native soil cover. This will result in an overburden which will subside over time.

1.7.3 Planting and care of trees

Trenches can be levelled at right angles at the time of planting. Trees can be planted using standard forestry practices. This study has found that trees planted on or between rows of entrenched sludge grow equally well, as sludge can be accessed laterally by roots. There is no need to plough the soil prior to sludge application.

1.8 Monitoring

It is the duty of the sludge user to ensure that both during and after the period that sludge is being actively utilised the safety of groundwater is not compromised and pathogenic material is safely contained. Baseline values of groundwater and soil should be established before sludge is entrenched at the site in order to provide a basis for assessing the impact of the entrenched sludge on the site over time. It should be kept in mind that unanticipated factors may arise which could alter the environmental impact of entrenchment during or after the period of use. For example:

- Heavy rains or flooding may cause pollutants and contaminants to rise to the surface or move further, more quickly or in higher concentrations through groundwater
- Encroachment of human settlement may reduce buffers, result in use of water near the entrenchment site for drinking which was not the case at the time of the site characterisation and increase the risk of human contact with contaminated areas
- Informal use of the site which may disturb sand covering which contains pathogens: e.g. sand winning, building, grazing

Should the sludge disposal site be affected by any of the above, sludge entrenchment should be suspended until such time as the conditions once again are conducive to continuation, if in fact this should occur.

1.8.1 Surface and ground water

Monitoring groundwater on the site should include both microbiology (faecal coliforms and E. Coli) and chemistry: alkalinity, organic nitrogen, nitrate-nitrogen, ammonium-nitrogen, chlorides, pH, COD, zinc, cadmium, copper and specific conductivity. Nitrate-nitrogen ($N0_3$) should not exceed 10 mg/ℓ in groundwater if the water will be used for drinking. In the event that the depth of the water table is less than 5m, monitoring should be done 3 monthly for dry sludge and monthly for liquid sludge and during the rainy season. Composite samples should be collected and analysed 20-50m upstream and downstream from the site and from any boreholes located within 1km of the site. Less frequent monitoring may be adequate where the soil clay content is greater than 35%, where dewatered sludge is entrenched above a water table deeper than 10m, or where liquid sludge is entrenched above a water table deeper than 20m. In some cases monitoring of groundwater may not be necessary due to the depth of the water table or other factors. This must be demonstrated through a study conducted by a qualified person. Detailed procedures and methodology for sampling and testing surface and groundwater are provided in the *Guidelines for the Utilisation and Disposal of Wastewater Sludge* (Volume 3, Appendices 1.3, 3 and 4.)

1.8.2 Soil

Monitoring of soil allows the movement of pollutants to be detected before they reach the groundwater, providing an early warning system. If sludge of pollutant class ***b*** or ***c*** is being used, soil must be monitored to ensure that metal content does not exceed the Maximum Permissible Level. (See Section 9.1.7.1). Increased concentrations of chloride provide a first indicator of the movement of elements and the possibility of contamination. The required frequency of monitoring will be determined by the clay content and pH of the soil and the water content of the sludge. If the site contains different soil types, different monitoring schedules may be necessary. Soils should be sampled at 100 mm intervals to a depth of at least 500mm below the bottom of the trench. Crops can be monitored for uptake of metals throughout the growing cycle by comparing foliage samples with samples from crops in similar soils.

1.9 Managing risks to environment and public health

If sludge has been deposited directly from the transport vehicle into trenches without spilling and covered with 300 mm soil, there is no need to restrict access to the site for the public who may use the forest recreationally. However, if any surface area has been contaminated by contact with sludge during application, those areas should be covered with an additional 300 mm of soil or fenced off for 3 years with signage clearly indicating a biohazard. If general contamination of the site has occurred, the entire site should be restricted for a period of 3 years with all workers entering the site wearing appropriate protective equipment and trained in procedures to protect themselves from infection with pathogens. Run-off from a site with surface contamination should be prevented from leaving the site by constructing cut-off trenches or bund walls down-gradient of the entrenchment site to intercept run-off. The bund wall must be high enough to intercept the surface run off with 0.5m to spare. The water must be recycled on site or treated before it is discharged. Similarly, if groundwater monitoring indicates elevated levels of pollutants in the leachate, leachate should be collected in a drainage pond and recycled or treated. Planting of vegetation can also be used to take up ground and surface water and slow movement from the site.

1.10 Closure of site

If entrenchment is to be discontinued at the site, an aftercare plan should be developed to manage potential ongoing risks to public health or the environment dependent on the planned future use of the site by the forestry company. Soil samples should be assessed for pathogen viability and levels of metals and nutrients which could migrate to the groundwater over time. If there does seem to be a risk, the plan should include ongoing monitoring until the risk is resolved and should address issues of ongoing restriction of the site to people, animals or agricultural use if needed to protect public health. If the final rotation of trees has been harvested, a final planting of trees or other plants can be used to assist with the management of both issues, preventing contact with pathogens by humans or animals through digging or farming and providing a sink for nutrients and limiting the movement of soil water which may contain pollutants.

2. Decentralised entrenchment

Entrenching VIP sludge, septic tank sludge, raw sewage or treated sewage at small, decentralised sites near the source of the sludge has a number of advantages over transport to and treatment at municipal wastewater treatment works (WWTW):

- Operations can be handled by a single small entrepreneur
- Lower transport costs
- Minimal overhead and infrastructure required
- Minimal skills required for daily operation (no complex processes or machinery to manage)
- Timber or fruit can be grown to benefit the local community
- Easier for small or rural municipalities to set up than hazardous waste sites (less red tape)

Deep row entrenchment of VIP sludge planted with trees can provide effective management of risks that would be involved with landfill disposal of VIP sludge:

- Direct entrenchment of sludge and burial the same day prevent contamination of surfaces or equipment with pathogens
- Small, dedicated sites with restricted access provide the control of a hazardous waste landfill without the red tape
- Solid waste disposed of in VIPs is automatically co-disposed of with sludge, with the potential for disposal of other solid waste with the sludge if needed
- Planting of trees creates a nutrient sink, reducing movement of potentially harmful nutrients from the trench
- Utilization of sludge by trees allows for repeated disposal of sludge at the same site over cycles of entrenchment and harvest, unlike landfills where re-use of site can only be done by adding additional layers

2.1 Site characterisation and selection

Requirements for site selection and characterisation in terms of environmental and public safety are the same as for deep row entrenchment for forestry and can be found in Section 1.3 of this document.

The following factors should be considered to assess the long term viability of the operation:

- Is the site large enough to accommodate the volume of sludge it will receive over the growth cycle (trench size/volume/size of community serviced/planting cycle – i.e. trenches that are planted are tied up for 6-9 years, can stockpiling be avoided?)
- Distance to source of sludge and means of transport (are VIPs that will need emptying in future years located further from the burial site?)
- Access to site for vehicles transporting sludge

2.2 Characterisation of sludge

While the characteristics of VIP sludge, in contrast to WWTW sludge, may be highly variable from pit to pit, the following assumptions can be made:

- ❖ Microbiological content: Pit sludge can be expected to contain high levels of viable pathogens and therefore can be assumed to have a microbiological classification of c.

- ❖ Stability: Unless a particular pit has been left unused for more than a year, VIP sludge contains both fresh sludge and sludge which may be several years old, representing all stability classes. Because it does contain some fresh, unstable sludge, it must be classified as Stability class c, requiring vector reduction which is provided by covering it with earth during entrenchment.

- Pollutant content: VIP sludge can be assumed to contain low levels of pollutants because it originates from domestic sources.

2.3 Designing and preparing the site

Trenches should be dug parallel to the ground contours. Trench spacing and dimensions will depend on the spacing of trees. It is advisable to prepare test trenches to ensure that the desired dimensions and spacing of trenches are feasible for the specific site conditions.

In terms of the impact on the degradation of the entrenched sludge over time, optimal dimensions for trenches are 800 mm deep and 600 mm wide, spaced 2.4 m apart edge to edge. This will allow for an application rate of 990 m^3per hectare with 300 mm backfill covering the sludge. The backfill over the trenches should be left heaped or ridged until planting to allow the backfill to settle and prevent erosion.

Monitoring boreholes should be located to intersect groundwater moving away from a disposal site.

Provision should be made at the site for cleaning, disinfection and storage of equipment and protective gear which may have come into contact with pathogens in the sludge. Facilities should be provided at the site for workers to shower and disinfect their hands as needed during and at the end of their work day. Workers should not be required to take work overalls or boots home for cleaning due to the risk of transmitting diseases from contaminated clothing.

2.4 Handling of sludge

Guidelines for safe transport and preventing the transmission of pathogens during the handling of sludge are provided in Section 1.6 of this document. VIP sludge should not be stored at the disposal site due to its vector attraction factor.

2.5 Application of sludge

Sludge should be delivered directly to trenches to prevent surface contamination and contamination of vehicles which may drive over sludge deposited at the side of trenches. The trenches are then backfilled with a minimum of 300mm native soil. Sludge should be covered the same day it is delivered to the trenches to prevent odour and attraction of vectors.

2.6 Planting of trees

Trees may be grown to produce timber for building, fencing, fuel or for the paper and pulp industry. Species which have a high demand for water will assist in absorbing the leachate produced by sludge, reducing the risks of groundwater contamination. Trees with some nitrogen-fixing capacity, such as wattle (*acacia mearnsii*) will benefit less from increased nitrogen loading through sludge. While fruit can be grown safely on trees planted on sludge buried on site at households, fruit should not be grown commercially for sale unless adequate measures are taken to disinfect the fruit from possible surface contamination.

2.7 Monitoring

It is the duty of the sludge user to ensure that both during and after the period that sludge is being actively utilised the safety of groundwater is not compromised and pathogenic material is safely contained. Baseline values of groundwater and soil should be established before sludge is entrenched at the site in order to provide a basis for assessing the impact of the entrenched sludge on the site over time. It should be kept in mind that unanticipated factors may arise which could alter the environmental impact of entrenchment during or after the period of use. For example:

- Heavy rains or flooding may cause pollutants and contaminants to rise to the surface or move further, more quickly or in higher concentrations through groundwater
- Encroachment of human settlement may reduce buffers, result in use of water near the entrenchment site for drinking which was not the case at the time of the site characterisation.

2.8 Surface and ground water

Monitoring of water on the site should include both microbiology (faecal coliforms and E Coli) and chemistry: alkalinity, organic nitrogen, nitrate-nitrogen, ammonium-nitrogen, chlorides, pH, COD, zinc, cadmium, copper and specific conductivity. Nitrate-nitrogen ($N0_3$) should not exceed 10 mg/ℓ if the water will be used for drinking. In the event that the depth of the water table is less than 5m, monitoring should be done 3 monthly for dry sludge and monthly for liquid sludge and during the rainy season. Composite samples should be collected and analysed 20-50 m upstream and downstream from the site and from neighbouring residential wells. Less frequent monitoring may be adequate where the soil clay content is greater than 35%, where dewatered sludge is entrenched above a water table deeper than 10m, or where liquid sludge is entrenched above a water table deeper than 20 m. In some cases monitoring of groundwater may not be necessary due to the depth of the water table or other factors. This must be demonstrated through a study by a qualified person. Detailed procedures and methodology for sampling and testing surface and groundwater are provided by DWA (Herselman & Snyman, 2009).

2.8.1 Soil

Monitoring of soil allows the movement of pollutants to be detected before they reach the groundwater, providing an early warning system. The required frequency of monitoring will be determined by the clay content and pH of the soil and the water content of the sludge. If the site contains different soil types, different monitoring schedules may be necessary. Soils should be sampled at intervals to a depth of at least 500 mm below the bottom of the trench.

2.9 Protecting public health and the environment

Animals and the public must be restricted from sites which are in use for burial of VIP sludge in order to prevent sludge being disturbed and pathogens spread. The site should be fenced securely with a gate that is locked when workers are not on the property. Stringent protocols must be followed by workers to prevent the spread of pathogens via vehicle wheels, tools or protective wear as they enter and exit the site.

2.10 Closure of site

If entrenchment is to be discontinued at the site, soil samples should be assessed for pathogens and metals, and viability and levels of metals and nutrients which could migrate to the groundwater over time. If there is a risk of ongoing contamination, an aftercare plan should be developed to manage potential threats to public health or the environment dependent on the planned future use of the site by the municipality or the company which owns the site until year soil sampling indicates that the levels of pathogens and metals have reduced to within acceptable limits. A final planting of trees or other plants on the site can assist with preventing contact with pathogens by humans or animals through digging or farming.

3. On-site burial of sludge (VIP)

Depending on the status of public health in the area, the sludge found in VIP latrines may contain significant levels of pathogenic organisms. This sludge is therefore regarded in South Africa as hazardous waste and it therefore becomes problematic to transport and dispose if it is concentrated in large volumes (as borne out by the preceding section of these guidelines). By far the least cost lowest risk disposal option is to bury the pit sludge close to the VIP where it was abstracted. This will not have any more impact on the groundwater than the VIP from which it was abstracted.

In future regulations may be promulgated to allow the concentration of pit sludge such that, for example, the waste from an entire small village could be entrenched on one site. However, South Africa’s Waste Management Act and Environmental Management Act currently preclude this option.

Sludge that is removed from a VIP pit can be buried on site if the home owner agrees and if an appropriate burial site can be found. On site burial of sludge reduces the risks (in terms of disease transmission) and costs of transporting sludge to a disposal or treatment site and eliminates the costs and difficulties involved with treatment or other disposal options. In order to utilise the sludge beneficially, trees which yield fruit, building material, shade or fuel can be planted above or alongside the buried sludge, with the following benefits:

- Nutrients which could potentially contaminate the groundwater are taken up by the trees
- Nutrients available in sludge improve the quality of fruit or wood, enhancing food security or economic security
- Householders are unlikely to expose the pathogens buried in sludge through digging, planting, or play, creating a health risk, if trees are planted over the burial site(s).

3.1 Site selection and preparation

No permit or notification of authorities is required for on-site burial of sludge from a VIP. However, as burial of sludge on site essentially involves digging small pits, the same variables should be considered for site selection as those for VIPs. In particular, the following factors should be considered in siting burial locations for sludge on site:

- If groundwater is present in the VIP pit, sludge should not be buried at locations lower on the site and should be placed in shallower holes.
- On-site burial should not be used in very sandy or gravelly soils because of the potential of groundwater contamination. (See Section 2.3)
- Burial holes should not be located on eroded banks or cutaways where activity could erode the vertical face into the sludge itself, exposing pathogens.
- Burial holes should not be located within 15m of a stream.

Holes or trenches should be prepared of adequate proportions to contain the sludge while also allowing for 300 mm of soil backfill on top of the sludge surface. This cover is partly to keep animals and people away from the sludge, and partly to provide space for trees to be planted above the sludge.

The volume of sludge removed from a full VIP pit will depend on the dimensions of the pit. Typically the volume will range between 1.5 m^3 and 2.5 m^3. Assuming a volume of 2.0 m^3, the recommended dimensions for a disposal pit are 2 m long by 1m wide by 1.3 m deep. Alternately, a pit which is 1.4 m by 1.4 m dug to the same depth will have the same capacity. Depending on soil conditions and the desired number and location of trees to be planted, sludge can also be buried in a trench or divided between several different planting holes. If a single disposal trench is used rather than a pit, the recommended dimensions would be 8m long by 0.5 m wide by 0.8 m deep.

3.2 Transfer of sludge from VIP pit to burial holes

Sludge may contain a variety of harmful pathogens. These can become airborne when the sludge is disturbed, meaning that they can settle on surfaces or enter workers' lungs. It is essential that workers removing sludge follow careful protocols to protect themselves as well as household surfaces. Contamination can occur by workers placing contaminated tools or gloves on household surfaces (walking around in contaminated boots, laying tools on the ground, benches, etc.), touching taps or door handles with contaminated gloves or hands, washing hands or equipment under household taps or borrowing householder tools or spilling sludge on the ground.

Basic principles to be kept in mind are:

- Pit emptiers must wear protective clothing (masks, overalls, gloves and boots)
- Work areas (lip of pit, area where tools and equipment are placed) must be protected with tarpaulins to prevent surface contamination
- Workers must not use tools belonging to the household for pit emptying
- Workers must not wash contaminated tools, clothing or hands at the household tap
- Any contamination which occurs must be remedied and the householder must be alerted

Pit emptiers should be provided with long handled tools, protective equipment for themselves and the site, bins for transporting the sludge and the necessary equipment to deal with contamination of surfaces should it happen (lime, clean shovel, stakes, tape).

After tarpaulins are placed on the lip of the pit, a disposal bin is placed on the tarpaulin. Workers remove the sludge from the pit into the bins using long handled shovels and rakes. Tools are placed on the tarpaulin and the bin is carried to the tarpaulin placed on the lip of the first burial hole.

3.3 Planting and care of trees

After sludge is placed in the hole, the top 300mm of the hole is backfilled with soil using a clean spade and the remainder of the soil that has been removed is heaped over the burial site. After trees have been planted over the holes, householders should be provided with information on how to care for their trees (pruning, diseases, etc.). The period of time that the buried sludge will provide an adequate nutrient supplement will depend on the tree species, nutrient values in the native soil and the quantity of sludge buried. Typically the tree will not require any supplementary fertilization for at least five years. After that, if necessary, householders can work manure and composted organic waste into the soil around the tree to provide additional nutrients.

3.4 Protecting public health and improving sanitation

Once sludge has been buried on site, clear instructions should be given to the householders that the sites should not be disturbed through digging or planting for a minimum of three years to prevent contact with buried pathogens which may still be viable.

If any contamination of surfaces has occurred during transfer of sludge from the pit to burial holes, these areas should be treated with lime, covered with 100mm soil and restricted with danger tape and stakes. The household should be told that the danger tape should be left for one month to prevent contact with concentrated lime.

Diarrhoeal diseases are a significant cause of the high rate of death among children under five years of age in South Africa. These diseases are spread through contact with faeces which happens when a person does not wash his or her hands with soap after using the toilet or when open defecation is practiced. In addition, it is very common for residents of communities with a history of poor sanitation to be infected with intestinal parasites which are also spread by contact with faeces. Both diarrhoeal diseases and intestinal parasites can pose a serious threat not only to young children but to the elderly and to individuals who are malnourished as a result of poverty or who have weakened immune systems as a result of HIV, TB or other illnesses. It is therefore recommended that municipalities take advantage of pit emptying as a natural point in the cycle of on-site sanitation provision to provide hygiene education and deworming medication to all members of a household. The household should be provided with a dose to be taken immediately and a follow up dose to be taken after six months.

APPENDIX B

An Extract from Notes on Organic Sources of Plant Nutrients

The following is an extract from notes, by A.D. Manson, given to students at the Cedara Agricultural College,

ORGANIC SOURCES OF PLANT NUTRIENTS

INTRODUCTION

Animal manures and compost have been used since the earliest civilizations for improving soil properties. In years gone by, these compounds were the main, if not only, source of nutrients for crop and vegetable production. However, since manures and composts contain relatively low concentrations of nutrients, and handling them is labour-intensive, they have been largely replaced by inorganic fertilizers as nutrient sources on many farms.

Organic fertilizers have two important effects on soil properties:

- they supply plant nutrients;
- they enrich the soil with organic matter, which improves soil physical properties (water infiltration, water retention, aeration, tilth).

Despite the modern tendency to overlook organic fertilizers, indications are that in many situations the use of these products could improve profitability. The rapid expansion of the poultry industry in recent years, for example, has led to large quantities of high quality manure becoming available at often very realistic prices. For farmers close to cattle feedlots, these are also often a good source of nutrients at reasonable cost.

Other organic materials that are sometimes used as fertilizers include those derived from sewage sludge, town refuse, seaweed and by-products and wastes from industrial processes (such as tannery wastes and filter cake from sugar mills). Of course, crop residues returned directly into the soil also contribute to the nutrients available to the next crop. This material includes straw, stubble and roots of cereals and grasses, and the parts of vegetable crops that are not marketed. In some cases, green manure crops are grown especially for ploughing in.

COMPOSTS

Composts are valuable products for supplying nutrients and for improving soil properties. Compost is a product of the decomposition of plant and animal wastes.

Dry or fresh plant and animal wastes can be applied directly to the soil, where they will eventually rot. However, because decomposition is often slow, it is better to compost them first. Other reasons for composting are: to destroy pests, disease organisms and weed seeds (this happens if sufficient heat is generated in the composting process); to reduce the potential for nitrogen immobilization (in the case of materials with a low N content); to reduce the chance of salt or ammonia burn (which may occur if high rates of fresh manures are used); to reduce or eliminate odours; and to produce a marketable product that can be used for potting, or in gardens.

Compost is made by constructing a heap of the waste material, which is kept compact and moist. The heap must be turned and mixed every few weeks to promote aeration. Aeration and moisture are essential for the activity of the microbes which are responsible for the decomposition process. Microbial activity may be speeded-up by the incorporation of small amounts of nitrogen fertilizer and lime. Compost is usually ready for use after 3 to 6 months. There is no limit to the amount that can be applied to the soil.

The making of compost is obviously labour intensive, and its use is therefore restricted largely to gardens and small plots. Unfortunately, people involved in production at this scale often neglect to use waste materials for composting and so overlook an extremely useful agent for soil improvement.

CROP RESIDUES

Crop residues can be important sources of nutrients, but they vary considerably in their composition. **Wheat straw and maize stubble** have low concentrations of nutrients (C:N ratio of 40:1 to 80:1, and contain 0.4-0.5% N, 0.1-0.2% P, and 0.3-0.4% K). They are, however, important sources of organic matter: the return of all straw or stubble to the soil can supply 2-5 (Is this t/ha? Luiz) of organic dry matter each year (the equivalent of 10-20 t/ha of farmyard manure). To accelerate stubble decomposition and prevent N immobilization, one unit of extra nitrogen can be incorporated with every 100-200 units of straw dry matter. **Residues from vegetable crops**, on the other hand, often contain considerable amounts of nutrients; For a cabbage crop with a marketable yield of 76 t/ha, the residues contained 104 kg N/ha, 12 kg P/ha, 70 kg K/ha, 235 kg Ca/ha, and 35 kg Mg/ha.

GREEN MANURE CROPS

Crops can be grown with the sole purpose of improving the soil for the following crop; the whole crop can be incorporated into the soil, or can be used as a mulch. Green manures are used to supply fresh organic matter to the soil, provide soil cover where erosion is a problem, add readily mineralisable nutrients (particularly N in the case of legumes) to the soil, and to prevent the leaching of nutrients by recycling them.

Species that have been found suitable for green manures are mustard (*Sinapis alba*), rye (*Secale cereale*), rape (*Brassica napus*), turnip rapes (*Brassica rapa* and crosses), ryegrasses (*Lolium* species), white clover (*Trifolium repens*), and vetch (*Vicia* species).

WASTES AND BYPRODUCTS

Products such as sewage sludge, composted garbage and tannery wastes have been used successfully as soil amendments, but it is difficult to generalise about these as they vary considerably, depending on their source. These products may also contain toxins or salts that may be harmful to crops, or to the consumer of the crop. These sources, therefore, generally need to be tested before they are used extensively for crop production. Other waste products, such as filter cake from sugar mills, composted garden refuse, and composted waste from fresh-produce markets, are known to be valuable soil amendments.

ANIMAL MANURE

The rest of this chapter was adapted from Klausner, Mathers & Sutton (1984) for the metric system, and discusses the basic principles regarding the use of manure in a soil fertility program, and presents general guidelines for managing manure for optimum crop production. Two South African publications that deal with the use of manure as a source of plant nutrients are: Funke, Knoesen & Venter (1984) and Knoesen (1979).

For centuries, farmers have spread livestock and poultry manure on the land as a way to increase soil productivity. Once applied to the soil, manure is decomposed by microorganisms forming humus and releasing essential elements for plant growth. The economic value of manure is related to its fertilizer replacement value, its organic matter content, its ability to improve soil physical properties and probably some unknown factors that enhance crop production.

Management is the key to efficient utilization of manure nutrients by a crop. Proper management should not only increase economic returns, but also reduce environmental concerns.

Nutrient content

Depending on the species, approximately 70-80 percent of the nitrogen (N), 60-85 percent of the phosphorus (P) and 80-90 percent of the potassium (K) fed to animals is excreted in the manure. The high nutrient return in manure permits a recycling of plant nutrients from crop to animal and back to the crop again.

The amount of nutrients contained in manure and their eventual uptake by plants will vary considerably from farm to farm. The major factors determining nutrient content and availability are:

(1) composition of the feed ration,

(2) amount of bedding and water added or lost,

(3) method of manure collection and storage,

(4) method and timing of land application,

(5) characteristics of the soil and the crop to which manure is applied, and

(6) the climate.

Table 1 shows the wide range in nutrient composition of manures sampled from numerous farms. Because of the large degree of variation, it is not advisable to use the average nutrient contents often seen in publications when determining manure application rates. Average values can be very misleading.

The most accurate way to determine nutrient content of manure is by laboratory analysis. The minimum analysis should include: percent dry matter, total nitrogen (inorganic N + organic N), phosphorus (P) and potassium (K).

Table 1 Range in Nutrient Analysis of Manure for Various Handling Systems (Bates & Gagon, 1981**)**

Animal species	Non-liquid systems			Liquid systems		
	N	P	K	N	P	K
	kg/t			kg/1000 L		
Dairy	2-8	0.4-3.5	0.8-13	0.4-6.1	0.1-1.1	0.2-5.8
Beef	2-10	0.4-2.9	1.2-12	0.7-4.4	0.1-1.5	0.5-3.0
Pigs	1-13	0.4-14	0.8-15	0.1-7.3	0.1-3.3	0.1-4.9
Poultry	2-55	0.4-21	0.8-23	4.2-9.0	0.1-4.8	1.3-3.9

The key to an accurate manure analysis is thorough mixing of the manure and proper sampling. For liquid manure, thoroughly agitate the contents of the storage and collect several samples as the storage is being emptied. For non-liquid manure, obtain samples either from representative loads leaving the storage or by taking them over a period of time when daily spreading. Place a composite sample in a plastic bottle, sealing tightly and freeze immediately. Some laboratories may recommend adding an acid. Freezing or acidifying is to preserve the sample since a considerable amount of nitrogen can be lost by improper handling.

Nutrient value

Manure contains all of the essential plant nutrients. The efficiency of their utilization by a crop depends on management of the land application program as well as the rate of biological breakdown of the organic material and release of plant-available nutrients. The value of the primary plant nutrients nitrogen (N), phosphorus (P) and potassium (K) is discussed here.

Nitrogen

There is no well-established, quick soil test to determine the effective N supply from organic matter in soils. Therefore, the N supply from manure in the soil must be estimated from research studies and applied to individual farm conditions.

Because of its chemical nature, manure N is more difficult to manage than other nutrients. There are two forms of N in fresh manure, namely unstable organic N and stable organic N. In either form, the organic N must be decomposed by microorganisms to inorganic N (mineral N) before it can be used by plants. This decomposition is called *mineralization*, and the resulting inorganic N is available for crop growth as nitrate (NO_3^-) and ammonium (NH_4^+).

The unstable organic N is present in urine as urea or uric acid and may account for more than 50 percent of the total N. Urea in manure is no different from urea in commercial fertilizer. It mineralizes very rapidly to ammonium (NH_4) and, in turn, converts very quickly to ammonia (NH_3) as the pH increases and the manure begins to dry.

Ammonia is extremely volatile, so exposure of manure on the barn floor, in the feedlot, in storage or after spreading increases the N loss. All of the ammonium N in manure is immediately available for plant growth. The value and amount of N utilized by the crop will depend on how much ammonium had been conserved during handling.

The more stable organic N is present in the faeces and is a more slowly released form of organic N than urea. The mineralization of stable organic N to the plant-available form occurs at two rates. The less-resistant organic N mineralizes during the year of application, whereas the more-resistant residual organic N mineralizes very slowly in future years. Repeated application to the same field results in an accumulation of a slow-release manure N source.

A decomposition series is commonly used to calculate the availability of N from organic sources. For example, the series .50-.10-.03-.01 gives a hypothetical rate of release of N from manure over the season of application and the three subsequent seasons. The series of numbers means that 50% of the total N is available during the year applied, 10% is mineralised in the second year, 5% in the third, and 1% each subsequent year.

The rate of microbial breakdown depends on soil characteristics, climatic conditions, animal species, moisture content, and method of manure storage. Very little local work has been done on the mineralization of manure, so it is suggested that the decomposition series given above is used.

Phosphorus and Potassium

Manure is an excellent source of P and K. When manure is applied at a rate to supply the N needed, the P and K applied will most likely be in excess of crop needs, unless the soil is deficient in one or both of the elements. Essentially all of the K is available for plant growth during the year applied. However, some of the P may be in the form of insoluble inorganic compounds or as organic P and, like organic N, must mineralize before it is available.

When establishing a crop, P is used more efficiently if banded close to the seed with the planter. Broadcasted manure is not an efficient method of applying P and, therefore, should not be used to satisfy the entire P requirement when band placement is critical. In the long term, the P in broadcasted manure is probably as efficiently used as the P in broadcasted fertilizer.

Potassium can generally be used efficiently by a crop as either a broadcast or band application. The K requirement can generally be met with the appropriate rate of manure.

There are reliable soil tests to determine the availability of P and K in the soil. The soil test level is a reflection of how much P and K has been applied from past manuring (&/or fertilizing) and this value should be used to determine the amount of fertilizer needed.

Economic Value

The effectiveness of manure as a fertilizer is based on the nutrients it contains that are not supplied in adequate amounts by the soil. Thus, the short-term fertilizer Rand value of manure is equal to the cost of the fertilizer that would have to be purchased had manure not been applied. In fields where the soil test levels for P and K indicates these nutrients are in adequate supply, only the fertilizer nitrogen value of the manure should be considered.

There may, however, be benefits other than the immediate fertilizer Rand value of manure: Lands that are only marginally adequate in P or K may require more P or K at a later date if it were not for manure inputs; manure may assist in the correction of soil acidity; soils with poor physical characteristics, such as poor tilth, cloddiness or low infiltration rates may be improved. The Rand value of these potential benefits is, however, often impossible to determine without actually applying manure to part of a land and comparing the results from that part of the land with those from the rest of the land.

When contemplating capital investments for manure handling, make a careful economic analysis of the change in your management. For instance, an expenditure that produces nutrient surpluses is not economical unless the surplus can be sold; on the other hand, an expenditure that markedly improves nutrient recycling, environmental quality or your management ability is a good investment.

Manure management will control how efficiently the nutrients in manure (especially nitrogen) can be used for crop production.

Land application

In a well-planned land application program, the rate of application is based on the nutrient requirements of the crop. Usually, the ratio of N to P to K in manure does not match the ratio of the amount of these nutrients needed by the crop; therefore, complete utilization is rarely accomplished.

When manure is applied at rates that provide more nutrients than are needed, these nutrients will accumulate in the soil. Further accumulation will occur from over-applying fertilizer. Thus, manure rates should be adjusted based on the nutrient availability in manure and the crop's requirement for that nutrient having the highest priority. The rate must be adjusted further if problems arise.

High rates of manure can oversupply certain elements in the soil to the point of affecting plant growth and animal nutrition. These problems are of regional importance; examples include salt injury and ammonia toxicity to plants, and nitrate poisoning and grass tetany in cattle. Aquatic growth in surface waters and high nitrate levels in drinking water can result from nutrient discharges into surface and ground waters.

Preventing such problems calls for a combination of appropriate soil and water conservation practices and properly managing the rate, timing and method of manure application.

One goal of a well-managed land application program is to develop a soil fertility program that utilizes manure to supply as much of the needed plant nutrients as possible, with commercial fertilizer then providing only what is additionally required. A particular kind of manure handling system does not, in itself, increase or decrease nutrient utilization by a crop; management does!

The first step in developing such a program is to determine the amount of nutrients collected in the manure; the second step is to estimate the availability of these nutrients; and the third step is to calculate a rate of application compatible with your crops' nutrient requirements. The following sections (along with the worksheets and examples) show how to match manure rates to crop production needs for your specific conditions.

Nutrient Collection

The amount of nutrients eventually applied to the land is not likely to be the amount originally present in the manure. Nutrient loss usually occurs during handling and storage either as liquid losses, ammonia volatilization or N, P and K leaching in exposed manure piles. Therefore, to account for all losses prior to land application, manure samples should be taken for analysis when manure is being readied for spreading or irrigation. Analysis of a series of such samples establishes an estimate of the nutrient content of manure on your farm. Periodic sampling should be done for adjusting the application rate.

Nutrient Availability

Nutrients in manure cannot be substituted for those in commercial fertilizer on a kilogram-for-kilogram basis. The reason is that some of the manure nutrients are not as readily available nor can they be as efficiently applied as those in fertilizer. Therefore, the amount of fertilizer N that manure can replace has to be calculated, whereas the P and K contribution can be measured by soil testing on a regular basis.

Note that the amount of available N increases greatly when the manure is spread just prior to planting and incorporated immediately. Remember, however that conserving ammonia is only important when N is limiting. Applying excessive amounts of N will not increase yields.

Rate of Application

It takes some planning and pencil-pushing to arrive at the application rate that best fits a particular cropping sequence. [You must] determine:

(1) the nutrient requirements of the crop to be grown,

(2) the manure's nutrient content,

(3) the manure application rate needed to supply the nutrient that has the highest priority, and

(4) the quantity of commercial fertilizer needed in addition to the manure.

[You must] determine your crop's N requirements in the absence of manure (because you need to know how much N must be added by a combination of manure and commercial fertilizer) and the crop's P and K requirements, using a soil testing and fertilizer recommendation service. The recommended N may be adjusted for residual soil N (See Manson, 1994).

[For example] a 120-kg/ha N requirement for maize could be met by a combination of applying and immediately incorporating 41 t/ha of manure in the spring, and adding 18 kg/ha of N in the starter fertilizer at planting. Depending on the region and soil test analysis, a starter fertilizer may be recommended even at a high rate of manure application.

After determining the rate for each field, add the total amount of manure needed and compare this to the amount collected. If there is an excess, divide it by the number of hectares receiving manure and increase the rate accordingly. If the rate of application becomes high enough to cause plant toxicity or pollution problems, additional land must be used to lower the application rate.

To determine number of spreader loads required per hectare, divide the per-hectare application rate by the weight or volume of manure in the spreader. The amount of liquid manure applied by irrigation can be measured by placing cans in the field to record the depth of water applied. There are 10 000 litres in one hectare-millimetre.

Keys to maximizing the value of manure

Timing and method of manure application determine the efficiency of nutrient recycling. Here are the major things to remember when applying manure.

- Incorporating manure immediately minimizes odours and ammonia loss. If manure supplies more N than is needed, some ammonia loss is unimportant as far as the crop is concerned. Ideally, ammonia should be conserved so that N can be applied to a large area. Incorporation of manure too far in advance of crop needs in high rainfall areas will result in N losses.
- Surface runoff and erosion must be controlled. Excessive tillage to incorporate manure on erosive soils in the fall and early winter may result in unacceptable soil and nutrient losses. Applying manure as close to planting as feasible reduces the potential for nutrient loss.
- As is the case with commercial fertilizer, manure must be spread uniformly to get consistent results.
- Amounts of commercial fertilizer should be reduced according to the nutrient value of the manure and the accumulation of nutrients in the soil from past manuring. Avoid over-applications.
- Your Fertilizer Advisory Service recommendations should be followed to ensure a proper balance of plant nutrients. Keep a record of nutrient levels in fields, and use this information as the basis for adjusting your manure management and soil fertility program.

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APPENDIX C

Soil Monitoring Results

Table 1 Analysis of soil samples taken from Sappi site

Sample ID	Sample density g/mL	P mg/kg dry	K mg/kg dry	Ca mg/kg dry	Mg mg/kg dry	pH (KCL)	Zn mg/kg dry	Mn mg/kg dry	Cu mg/kg dry	Org.C %	N %
D1	0.85	2.4	14.1	77.6	42.4	4.35	0.9	2.4	12.7	0.9	0.23
D2	0.97	4.1	18.6	80.4	83.5	3.81	7.2	1.0	23.3	0.5	0.12
D3	1.04	6.7	43.3	593.3	261.5	4.48	5.4	7.7	5.4	0.5	0.21
D4	0.9	4.4	27.8	404.4	200.0	4.47	3.7	2.2	6.9	0.5	0.27
D5	0.84	8.3	8.3	41.7	21.4	5.05	0.6	2.4	12.9	0.5	0.16
D6	0.83	2.4	16.9	37.3	22.9	4.72	0.5	1.2	7.7	2.6	0.3
D7	0.79	1.3	45.6	88.6	25.3	4.77	0.4	2.5	7.5	6	0.59
D8	0.89	1.1	9.0	102.2	153.9	5.73	4.8	5.6	20.1	0.8	0.27
D9	0.92	1.1	4.3	22.8	29.3	6.22	0.1	2.2	3.2	0.5	0.31
D10	0.89	2.2	9.0	14.6	13.5	4.93	0.3	1.1	3.5	1.2	0.22
D11	0.98	4.1	16.3	284.7	196.9	4.3	1.8	4.1	10.1	0.5	0.15
D12	0.94	2.1	16.0	518.1	247.9	4.15	1.3	1.1	9.8	0.5	0.13
D13	0.94	3.2	14.9	34.0	21.3	6	1.5	3.2	1.2	0.9	0.27
D14	0.95	1.1	10.5	60.0	61.1	5.17	0.3	2.1	2.1	0.5	0.17
D15	0.96	1.0	15.6	43.8	47.9	5.21	0.5	7.3	1.6	0.5	0.16
D16	0.95	1.1	6.3	31.6	63.2	5.73	0.2	3.2	1.7	0.5	0.14
D17	0.93	1.1	6.5	25.8	14.0	5.73	7.0	3.2	1.7	0.5	0.19
D18	0.91	2.2	7.7	11.0	0.0	4.78	0.3	2.2	2.2	0.5	0.18
D19	0.91	4.4	12.1	36.3	23.1	4.81	0.3	3.3	3.5	0.5	0.12
D20	0.98	1.0	11.2	27.6	60.2	4.74	0.0	2.0	1.2	0.5	0.14
D21	0.93	1.1	4.3	45.2	77.4	6.22	0.3	4.3	6.8	1.4	0.3
D22	0.88	1.1	9.1	34.1	6.8	4.53	0.0	2.3	4.4	1.4	0.25
D23	0.96	1.0	4.2	36.5	0.0	5.26	0.0	3.1	2.1	0.5	0.19
D24	0.98	1.0	5.1	0.0	4.1	6.72	0.0	2.0	1.0	1.6	0.44
D25	0.89	2.2	7.9	2.2	0.0	5.5	0.0	5.6	1.7	1.7	0.35
D26	0.72	2.8	27.8	55.6	13.9	4.35	7.5	1.4	4.0	5.9	0.47
D27	0.8	2.5	20.0	120.0	56.3	4.36	0.4	1.3	4.5	4.3	0.35
D28	0.88	2.3	4.5	84.1	58.0	6.06	0.2	2.3	2.2	1.5	0.43
D29	0.97	1.0	5.2	61.9	23.7	6.24	0.3	5.2	2.4	1	0.27
D30	0.87	1.1	10.3	39.1	6.9	4.8	0.3	2.3	3.6	4.2	0.35
J1	0.93	5.4	45.2	131.2	44.1	3.98	0.9	3.2	1.3	3.4	0.23
J2	0.81	3.7	32.1	30.9	2.5	3.99	0.1	1.2	1.5	2.7	0.25
J3	0.84	10.7	91.7	36.9	17.9	3.96	0.5	1.2	2.1	4.7	0.33
J4	0.83	7.2	50.6	78.3	16.9	3.93	0.4	2.4	1.9	4.2	0.32
J5	0.87	5.7	41.4	31.0	40.2	3.97	0.5	2.3	0.8	2.2	0.32
A1	0.85	1.2	20.0	27.1	47.1	3.99	0.2	1.2	0.6	1.2	0.14
A2	0.76	11.8	31.6	59.2	51.3	3.82	1.1	2.6	2.5	6	0.45
A3	0.83	7.2	36.1	36.1	31.3	3.94	0.6	1.2	1.1	1.7	0.14
A4	0.85	5.9	35.3	20.0	20.0	3.98	0.5	1.2	0.9	1.5	0.15
A5	0.85	2.4	23.5	15.3	18.8	3.97	0.4	1.2	0.6	0.9	0.16
A6	0.88	1.1	22.7	23.9	28.4	3.92	0.1	1.1	0.7	1.1	0.14
A7	0.86	1.2	15.1	37.2	17.4	3.98	0.2	1.2	0.6	1.6	0.15
A8	0.86	3.5	25.6	93.0	59.3	4	0.2	1.2	0.6	0.8	0.15
B1	0.72	20.8	63.9	329.2	43.1	3.86	0.7	4.2	3.1	6	0.52
B2	**0.8**	**300.0**	**107.5**	**947.5**	**176.3**	**3.72**	**62.6**	**23.8**	**20.1**	**5.4**	**0.43**
B3	0.75	20.0	130.7	96.0	21.3	3.78	0.4	4.0	3.3	6	0.44
B4	0.9	4.4	30.0	90.0	60.0	3.97	0.8	7.8	1.0	2.1	0.33
B5	0.86	2.3	24.4	32.6	57.0	4.13	0.3	1.2	1.0	2.6	0.19
B6	0.86	8.1	54.7	122.1	59.3	3.94	0.3	5.8	1.9	3.8	0.32
B7	0.89	4.5	34.8	30.3	93.3	3.97	0.2	2.2	1.7	3.7	0.31
B8	0.94	14.9	85.1	256.4	101.1	4.11	3.2	12.8	1.3	1.6	0.52
C1	0.85	51.8	42.4	96.5	84.7	3.89	5.1	3.5	4.0	2	0.23
C2	**0.87**	**344.8**	**74.7**	**731.0**	**273.6**	**3.8**	**46.2**	**16.1**	**18.6**	**4.6**	**0.42**
C3	0.91	5.5	35.2	0.0	47.3	4.15	0.4	1.1	0.7	1.4	0.32
C10	0.82	29.3	62.2	125.6	90.2	3.97	3.0	4.9	4.5	4.1	0.31
C11	0.85	8.2	50.6	38.8	49.4	4.01	0.7	1.2	1.8	1.7	0.32
C12	0.81	12.3	63.0	103.7	40.7	3.85	1.0	3.7	3.8	3.2	0.28

For a discussion of the above results refer to Section 3.5.3 of the main report.

APPENDIX D

Umlazi Groundwater Monitoring Results

Introduction

Between October 2008 and October 2009 over one thousand cubic metres of pit latrine sludge was buried at the Umlazi entrenchment site (see Section 3.4 of this report). Figure 1 below shows the position of five monitoring boreholes which were constructed between the entrenchment site and the nearby Umlazi River.

Figure 1 Umlazi Entrenchment Site (under main body of trees), monitoring boreholes BH1 to BH5 and Umlazi River (location shown by pale green water hyacinth)

The 25 metre deep boreholes were cased with uPVC pipe with a 3 metre slotted section at the bottom. A steel section cased in concrete was used to top off the well, and this was fitted with a lockable steel cap (Figure 3). Despite this precaution from time to time the locks and the caps were stolen and had to be replaced. A battery powered submersible pump was used for sampling, and the contents of the well were thoroughly purged before sampling to ensure that the sample represented the groundwater around the well and not water which had been sitting in the well (Figure 3).

The wells were monitored from October 2008 to February 2011, and the results are recorded below. This work was carried out by UKZN's doctoral student Babatunde Bakare, assisted by Dr Kitty Foxon.

Figure 2 Sampling water from one of the monitoring wells at the Sappi site.

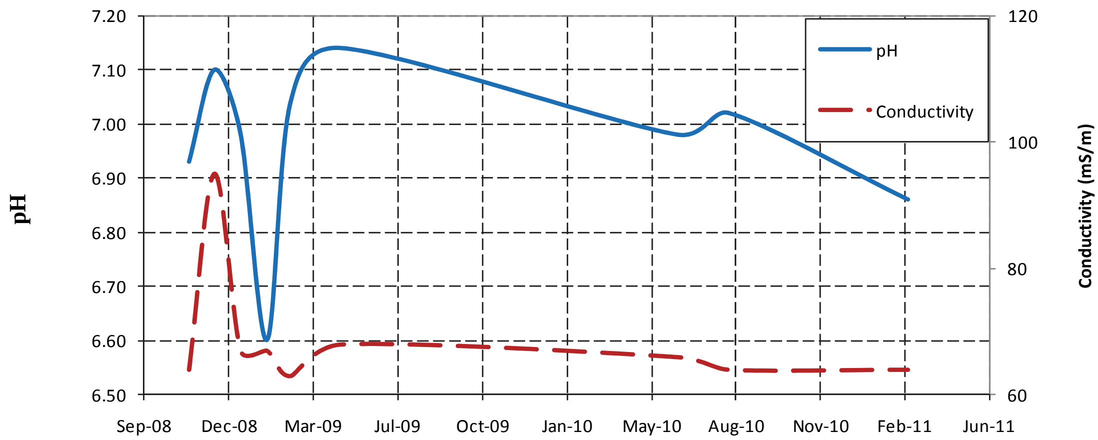
Figure 3 The tops of the wells were fitted with a lockable steel cap.

The results obtained from the laboratory analysis of the water samples collected from each of the monitoring boreholes is been compared with the South African Bureau of Standards No 241 specification. From May 2009 up until June 2010 sampling was not carried out on Borehole 1 because the lock on the borehole was vandalized and there was also a fire disaster at the EWS lab which affected the sampling from all boreholes between February 2010 and June 2010. The result of the laboratory analysis of each determinant in the water samples collected from each of the monitoring boreholes is presented as follows:

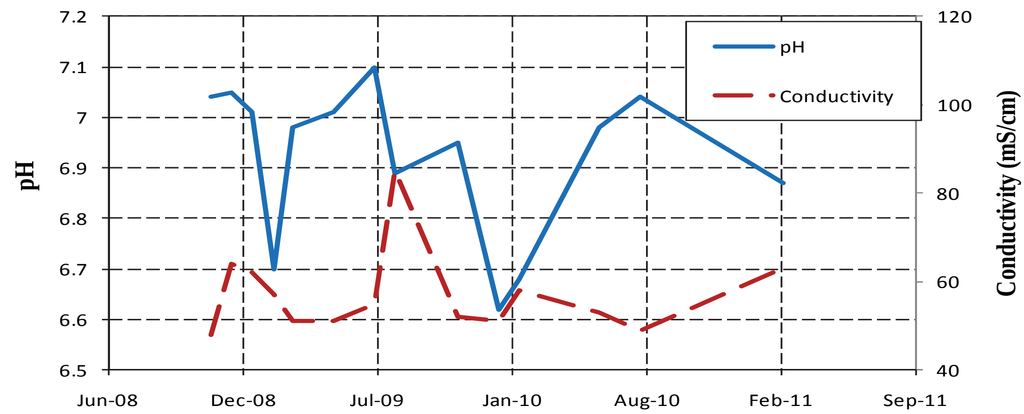
pH and Conductivity

The pH of the water samples collected from each of the boreholes has remained consistent between slightly acidic pH and neutral pH since the commencement of the sampling process. This range of pH values obtained from water samples collected from each of the monitoring boreholes at the entrenchment site falls within the recommended maximum limit of pH value of 6-9 specified by the SABS specification for drinking water. The conductivity results obtained from the water samples from each of the boreholes has also been below the maximum allowable limit of 300 mS/m specified by the SABS specification for drinking water. Plot of the pH and conductivity results of groundwater sampled from the 5 boreholes at the entrenchment site are presented below

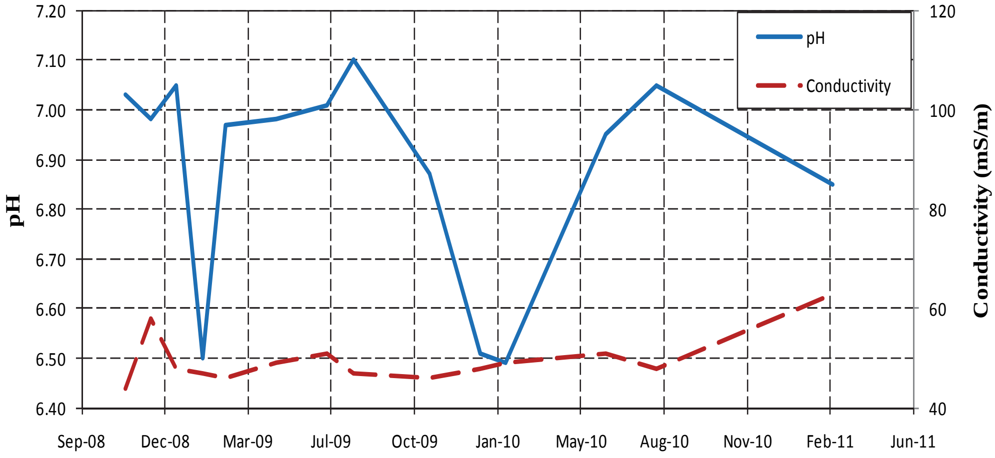
BH1



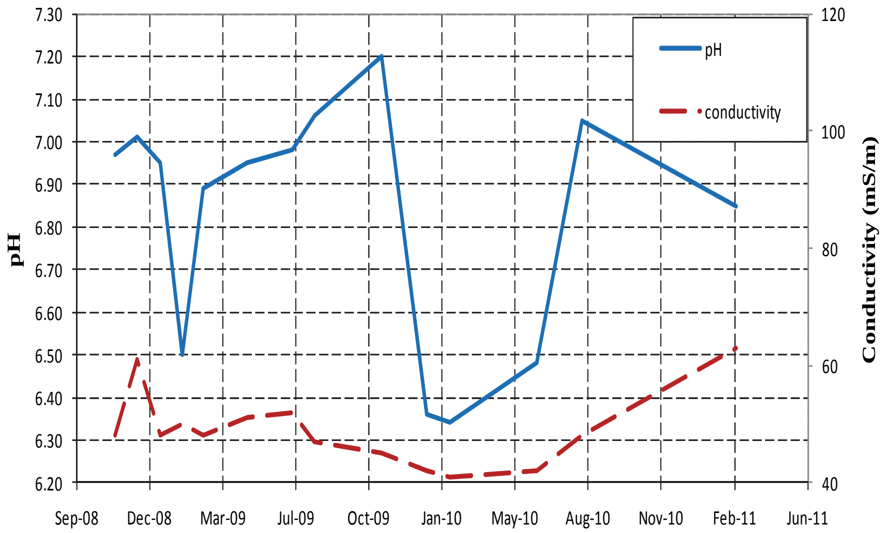
BH2



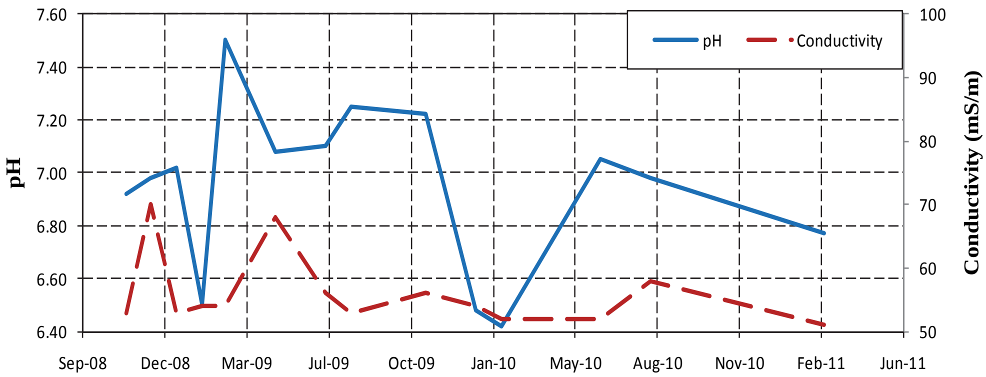
BH3


pH
Conductivity
pH
Conductivity (mS/m)
7.20
7.10
7.00
6.90
6.80
6.70
6.60
6.50
6.40
120
100
80
60
40
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

BH4


pH
conductivity
pH
Conductivity (mS/m)
7.30
7.20
7.10
7.00
6.90
6.80
6.70
6.60
6.50
6.40
6.30
6.20
120
100
80
60
40
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

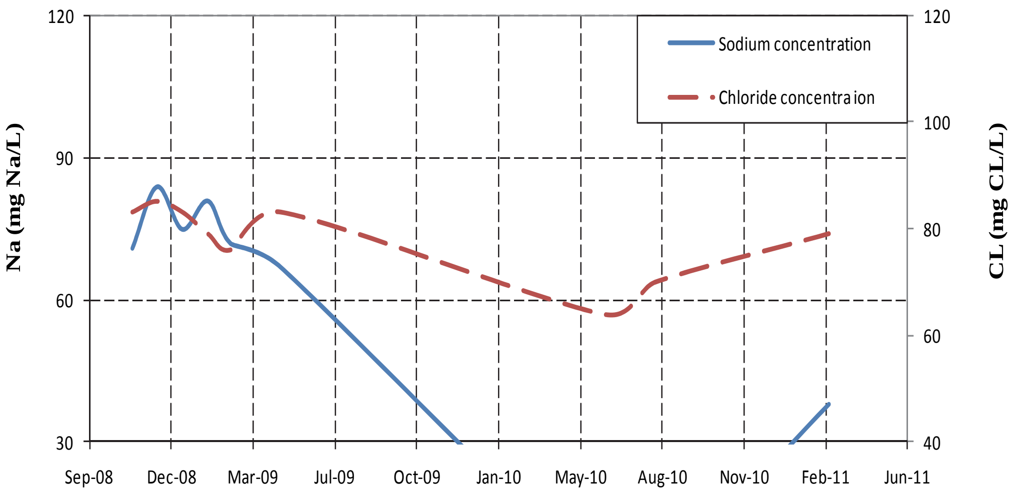
BH 5


pH
Conductivity
pH
Conductivity (mS/m)
7.60
7.40
7.20
7.00
6.80
6.60
6.40
100
90
80
70
60
50
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

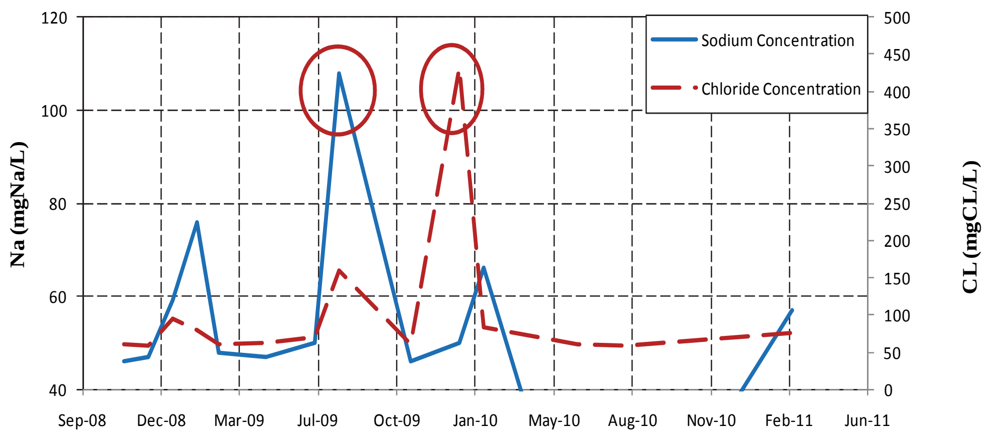
Sodium and Chloride concentrations

It is observed that the concentration of sodium and chloride ions obtained from the analysis of the collected water samples from each of the monitoring boreholes had similar values except for borehole number 2 in which at some point high values in the chloride and sodium ions was measured. It is believed that this high values obtained might be has a result of analytical error or that this values were incorrectly recorded result as this high value do not correspond to the sodium or chloride measurements for the samples. However, the values obtained for sodium concentration for each of the boreholes since the commencement of the sampling process has been below the maximum allowable limits of 400 mg/l specified by the SABS specification for drinking water. The values obtained for the chloride concentration from the analysis of the water samples collected from each of the boreholes since the commencement of the sampling procedure also falls below the maximum allowable limit of 600 mg/l specified by the SABS specification for drinking water. Plot of the sodium and chloride concentration results of groundwater sampled from the 5 boreholes at the entrenchment site are presented below

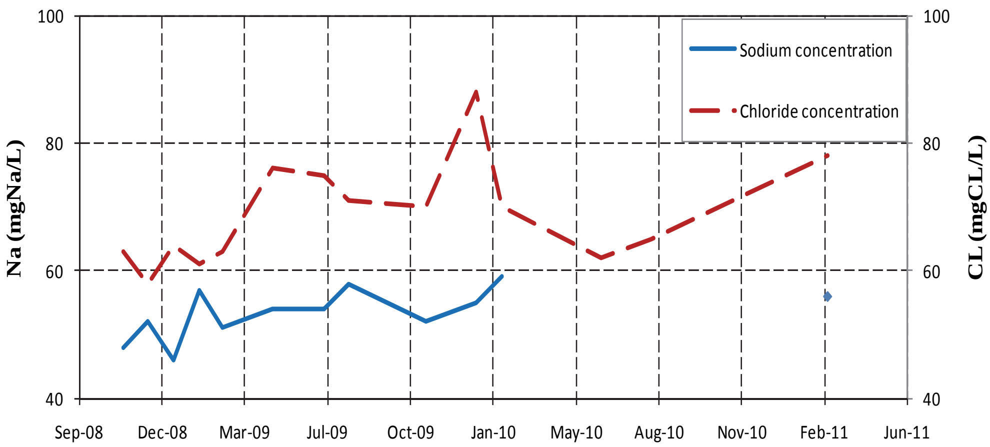
BH1



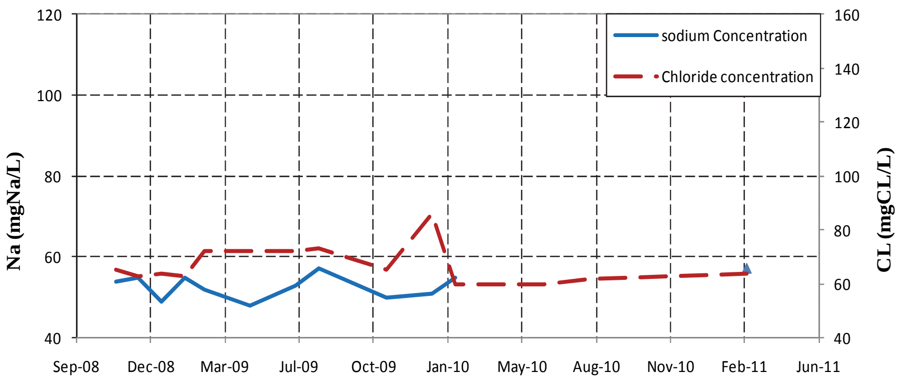
BH2



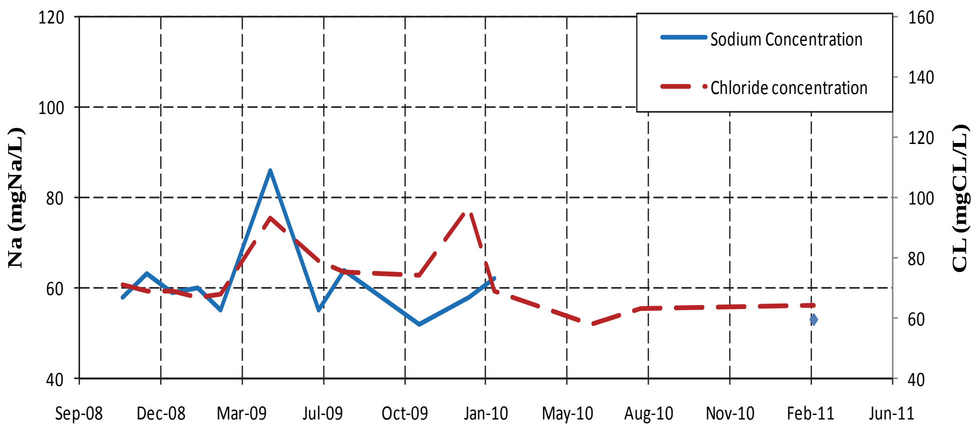
BH3


Sodium concentration
Chloride concentration
Na (mgNa/L)
CL (mgCL/L)
100
80
60
40
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

BH4


sodium Concentration
Chloride concentration
Na (mgNa/L)
CL (mgCL/L)
120
100
80
60
40
160
140
120
100
80
60
40
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

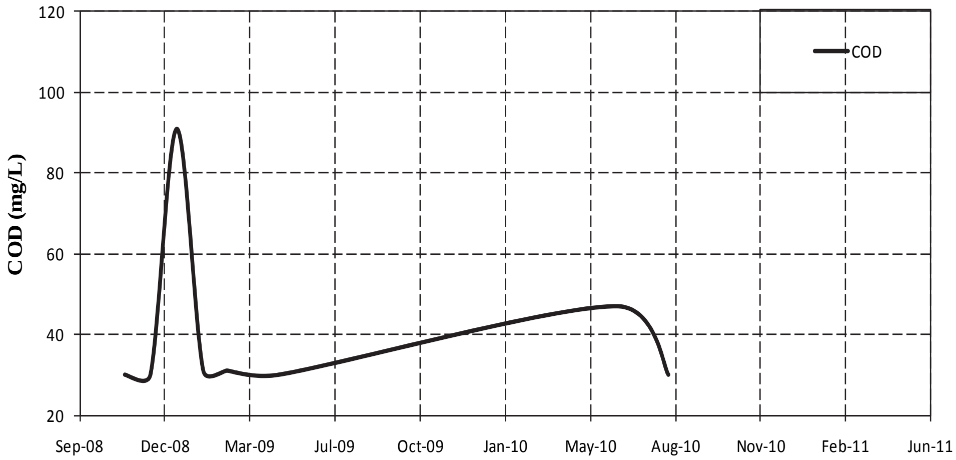
BH5


Sodium Concentration
Chloride concentration
Na (mgNa/L)
CL (mgCL/L)
120
100
80
60
40
160
140
120
100
80
60
40
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

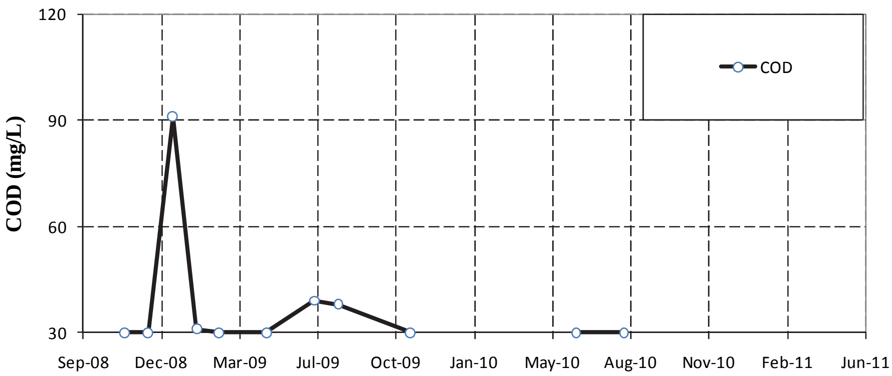
Chemical Oxygen Demand

COD results for the water samples collected from the five boreholes were somehow within same range for all of the boreholes. Since the commencement of the sampling procedure the COD of the water samples have been significantly low and has been within the maximum allowable effluent discharge target as presented in DWAF (1999). Plot of the chemical oxygen demand results of groundwater sampled from the 5 boreholes at the entrenchment site are presented below.

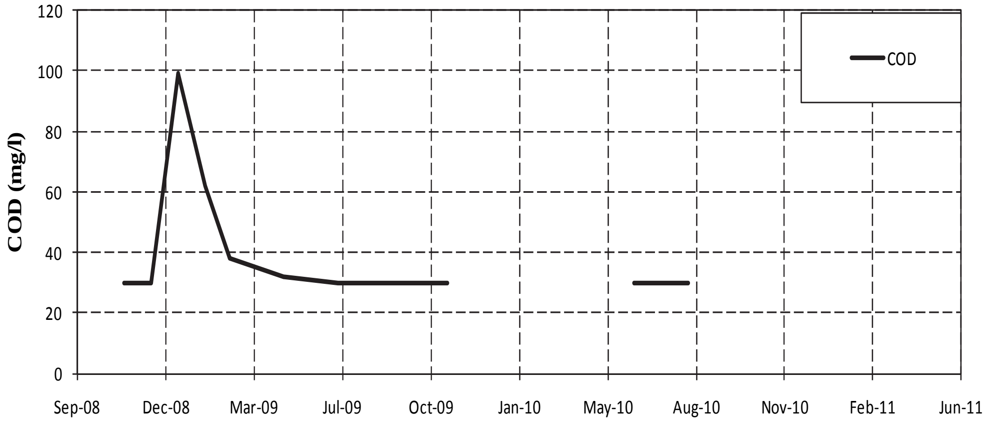
BH1



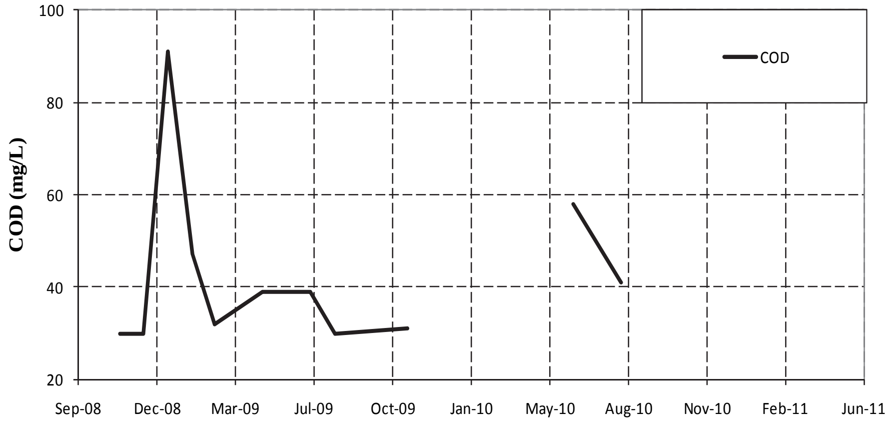
BH2



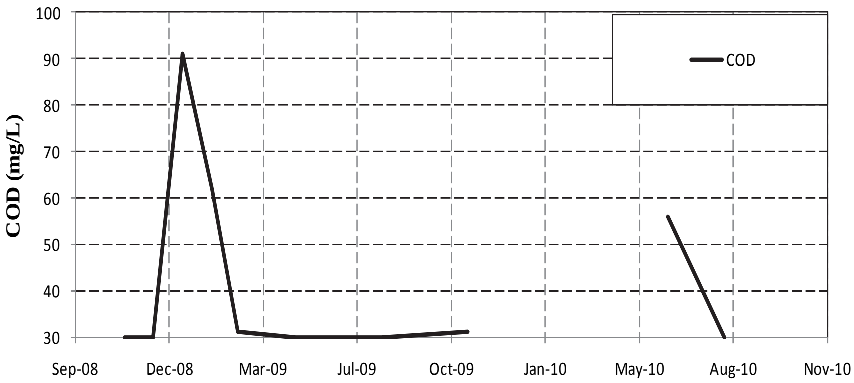
BH3


COD
COD (mg/l)
0
20
40
60
80
100
120
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

BH4


COD
COD (mg/L)
20
40
60
80
100
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

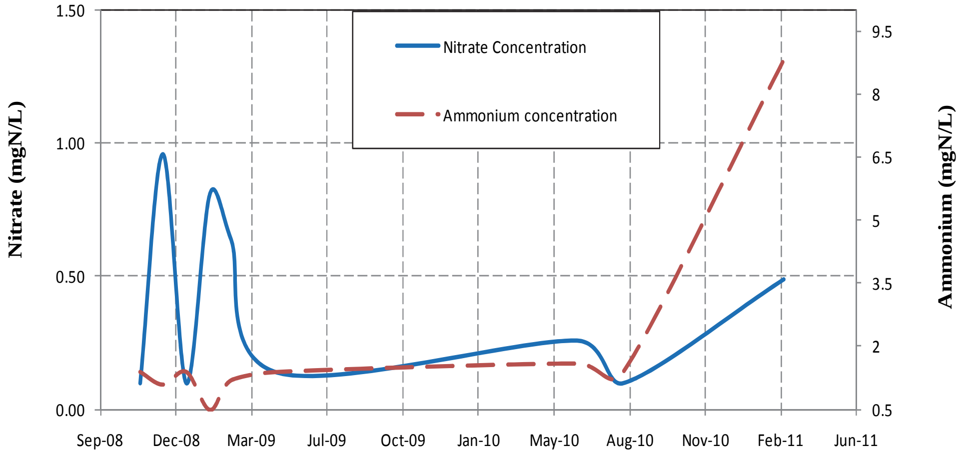
BH5


COD
COD (mg/L)
30
40
50
60
70
80
90
100
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10

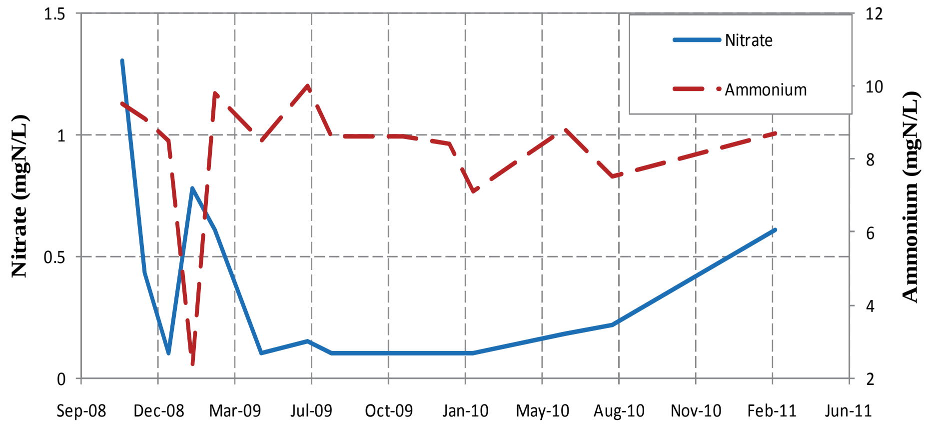
Nitrate and Ammonium concentration

Nitrate and ammonium concentration usually serves as the determinant of pollutant in most groundwater water monitoring programme. However the results obtained from the analysis of water samples collected from each of the five boreholes at the VIP latrine entrenchment site has been consistently lower and within the maximum allowable limits of 10 mgN/L for nitrate and 15 mgN/L for ammonium as specified by the SABS specification for drinking water. Plot of the Nitrate and ammonium concentration results of groundwater sampled from the 5 boreholes at the entrenchment site are presented below

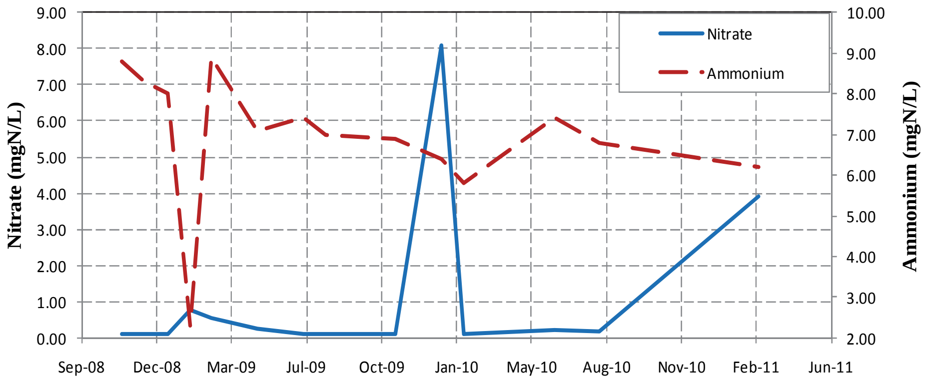
BH1



BH2

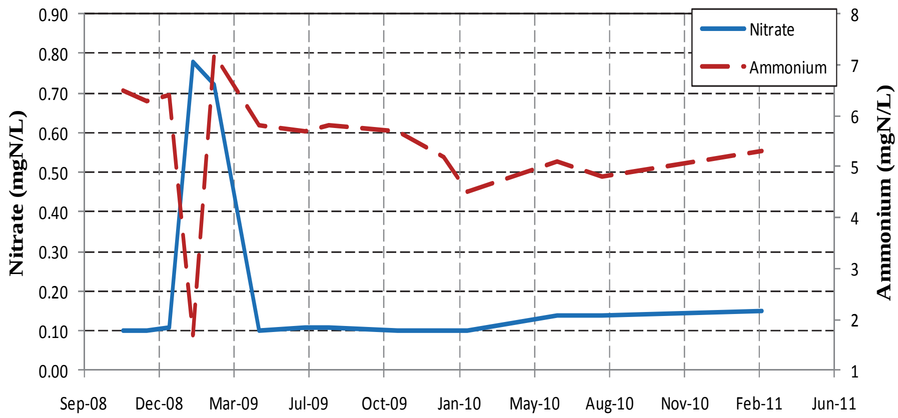


BH3



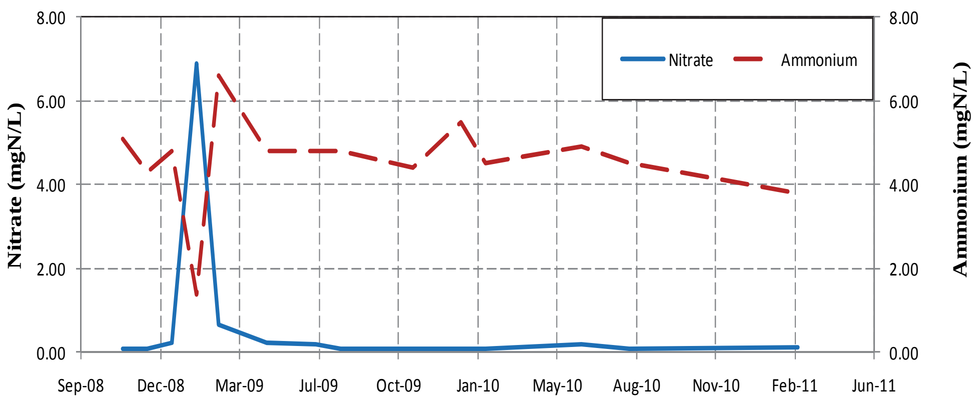
Nitrate
Ammonium
Nitrate (mgN/L)
Ammonium (mgN/L)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

BH4



Nitrate
Ammonium
Nitrate (mgN/L)
Ammonium (mgN/L)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
8
7
6
5
4
3
2
1
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

BH5

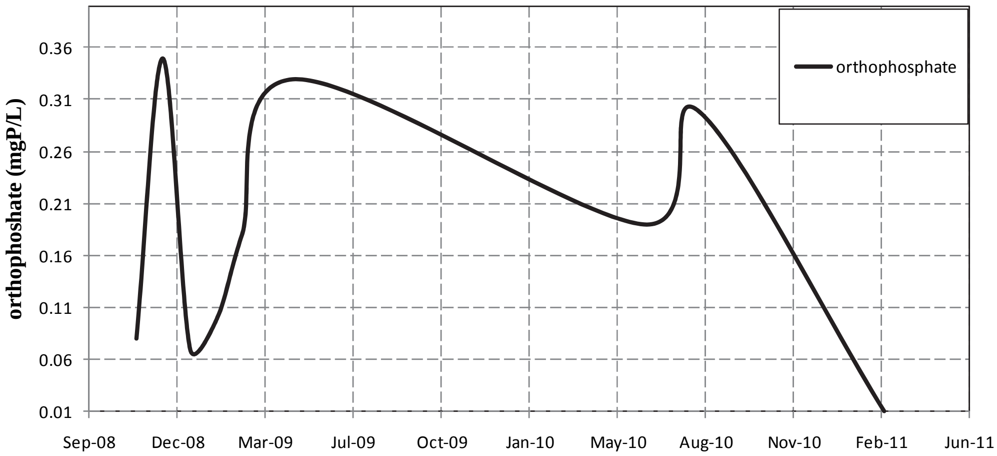


Nitrate
Ammonium
Nitrate (mgN/L)
Ammonium (mgN/L)
8.00
6.00
4.00
2.00
0.00
8.00
6.00
4.00
2.00
0.00
Sep-08
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11
Jun-11

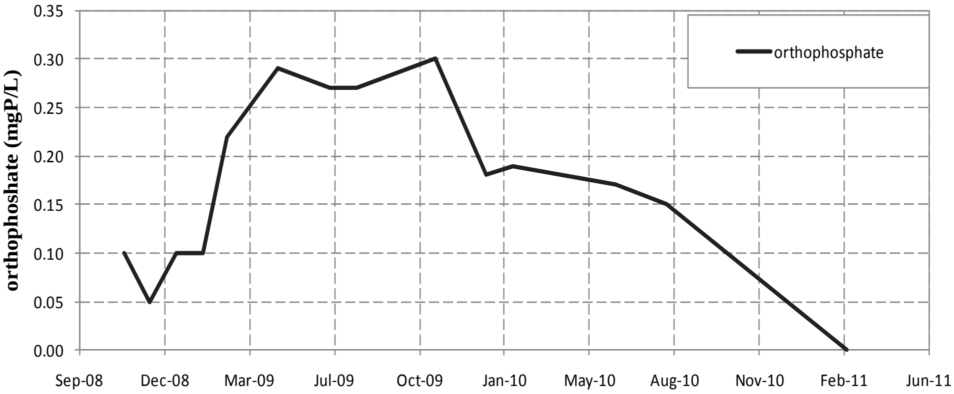
Orthophosphate

It was speculated that phosphate and its compounds might possibly contaminate the surrounding groundwater at the entrenchment site since the majority of the households serviced with VIP latrines usually pour their laundry water into the pits and phosphate and its compounds are usually added to detergent in order to enhance the cleaning ability of household detergent. However, since the commencement of the groundwater monitoring programme the results obtained from the laboratory analysis of collected water samples from the five monitoring boreholes has never exceeded the recommended maximum limit of 10 mgP/L specified by SABS specification for drinking water. Plot orthophosphate results of groundwater sampled from the 5 boreholes at the entrenchment site are presented below

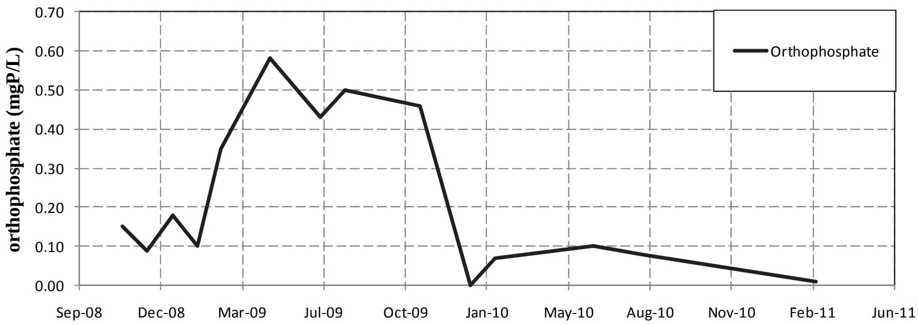
BH1



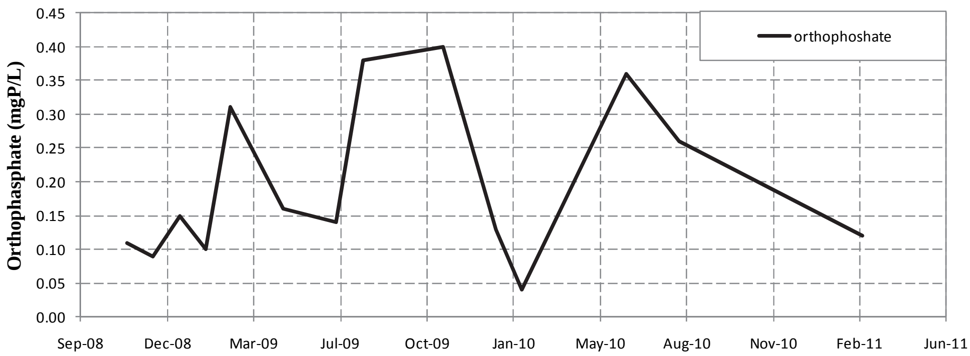
BH2



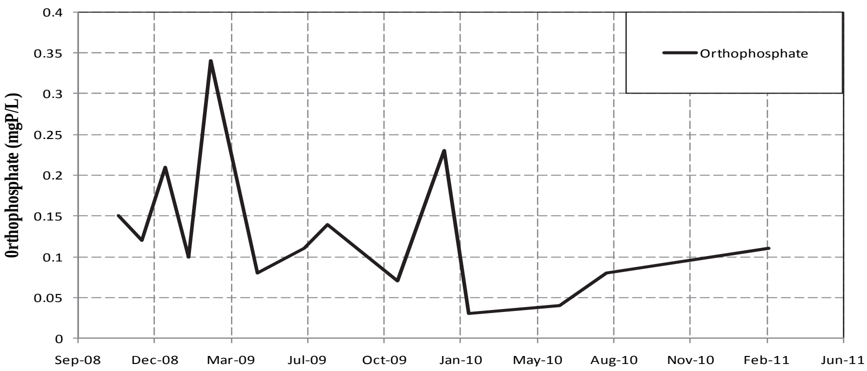
BH3



BH4



BH5



<u>Bacteriological Results</u>

The bacteriological analysis involved analysis E-coli, total coliforms and also total organisms in the water samples collected from the five monitoring boreholes from the commencement of the sampling programme. Interestingly it was found that since the commencement of the sampling programme at the entrenchment site the E-coli count from the water samples has been zero and the other bacteriological tests were below the detection limits for this tests.

Conclusion

The primary objective was to monitor the characteristics of the surrounding groundwater so as to determine the effect of entrenchment on the sludge content as well as the surrounding groundwater. **Table 1** presents a summary of the results obtained from the groundwater monitoring programme. Monitoring of groundwater at the entrenchment site involved regular sampling of water from the five monitoring boreholes at the entrenchment site and laboratory analysis of the collected water samples to determine any changes in the characteristics of the water samples with time. This was carried out to establish any migration of pollutant into the groundwater which might be as a result of the entrenchment activities. Selected pollutant determinants which are measurable were chosen and monitored to see if there were any changes. This selected determinant includes pH, Conductivity, sodium ions, chloride ions, nitrates, ammonium concentration, orthophosphate and chemical oxygen demand. Since the commencement of the monitoring programme no significant or defined trend in all the measured determinants was observed.

Furthermore, since the commencement of the groundwater monitoring programme, none of the determinants were found to exceed allowable limits as compared with the SABS specification for drinking water as well as the DWAF Discharge standards into a water course.

Table 1 Summary of results obtained from groundwater monitoring programme. Data are presented as [min, max]

Parameters	Units	BH 1	BH 2	BH 3	BH 4	BH 5
pH		[6.60,7.14]	[6.70,7.1]	[6.50,710]	[6.50,7.20]	[6.5,7.5]
Conductivity	mS/m	[63, 95]	[48,85]	[44,58]	[45,61]	[53,70]
DO	mg/L	[1.03,3.20]	[1.10,3.05]	[0.35,3.10]	[0.30,3.20]	[0.2,3.4]
Sodium	mgNa/L	[67,84]	[46,108]	[48,58]	[48,57]	[55,64]
Chloride	mgCL/L	[75,86]	[58,160]	[58,76]	[63,73]	[68,93]
Nitrates	mgN/L	[<0.1,0.96]	[<0.1, 1.3]	[<0.1,0.79]	[<0.1,0.78]	[<0.1,6.9]
Ammonium	mgN/L	[<0.5,0.14]	[2.3, 10]	[2.30,8.80]	[1.7,6.5]	[1.4,6.6]
Ortho-phosphate	mgP/L	[0.07,0.35]	[0.05,0.30]	[0.09,0.58]	[0.09,0.40]	[0.08,0.34]
E-coli	Cfu/100 ml	0	0	0	0	0
COD	mg/l	[<30,91]	[<30,91]	[<30,99]	[<30,91]	[<30,91]

APPENDIX E

Pathogen Survival Data

1. PREVIOUS WORK

Work carried out during Project K5-1829 indicated that pathogens buried in soil die off over a period of two to three years. Figure 1 below is from the final report for Project K5-1829 (Figure 5.56, page 71).

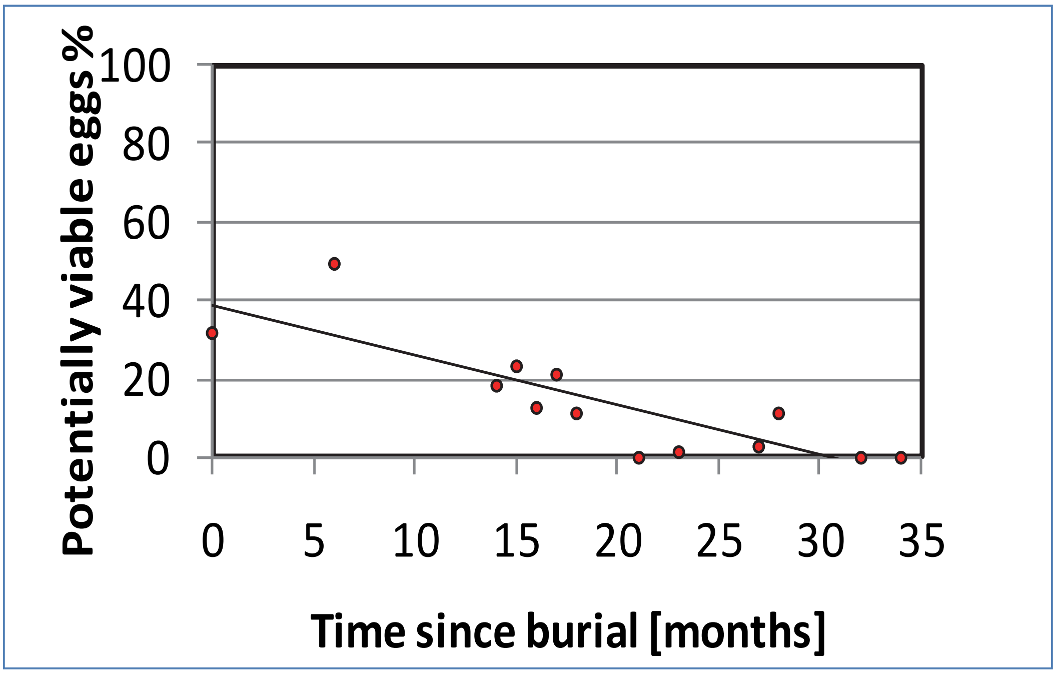


Figure 1 Die off of Ascaris over the first 30 months of burial at the Umlazi site

2. UMLAZI SITE

In January 2013, 88 new samples were taken from the Umlazi experimental site. Of these, 30 were taken from pit sludge, 28 were taken from the ground surface where the sludge had been buried and 30 were taken from the ground surface in the vicinity of the experimental site as a control. The purpose behind each of these three sets was as follows:

Sludge samples: to determine if any pathogens had survived in the sludge itself

Ground surface: to determine if the ground surface where the sludge had been buried posed a public health risk

Background surface: As a control for comparison with the ground surface above the sludge

Whereas in earlier testing a soil auger had been used to sample the sludge, the sludge was by this time so decomposed that sometimes field workers found it difficult to know whether they had really found the sludge or not. For this reason open pits were dug to reach the sludge layers. All pits were photographed.

Figure 1 After four years' burial the sludge is hard to distinguish from the surrounding soil (the plastic is a good clue)

The samples were analysed by Colleen Archer and Val Kelly at the School of Biological Sciences for *Ascaris*, *Trichuris Trichiura* and *Taenia.* Note that all Trichuris and Taenia were dead – the numbers merely indicate the numbers of dead ova observed. Hawksworth and Foxon have previously observed that fresh VIP sludge in Durban typically contains 200 to 1000 Ascaris ova per gram. In the 30 samples detailed in Table 1, a total of 1626 Ascaris ova have been observed in a total of 300 g of sludge. Of these 1626 ova, only one was observed to be motile, and the rest were undeveloped, immotile, infertile, necrotic or dead (with 11% being necrotic and 87% being dead). It is not impossible that the sampling method (digging to reach the sludge) might have contaminated the material at depth, which would explain the one motile ovum discovered. It does therefore seem safe to conclude that pathogens in buried sludge die off within 3 to 4 years. As there would be no need or intention to dig up the sludge after burial, it can by extension be concluded that burial is a safe means of sludge disposal.

A further 28 samples were taken from the soil surface in the area where the sludge was buried (Table 2). The soil surface is of more interest from a public health point of view, as this is where the public might be exposed to the risk of infection. Due to the low counts of ova, 20 gram samples were analysed. From the 28 samples a total of 75 Ascaris ova were recovered from the 560 g of sludge, 72 of which were dead and 3 were necrotic. In one of the samples 752 possibly viable Taenia (tapeworm) ova were observed. However, given that Taenia ova do not normally survive in the open for this length of time, it is likely that these ova were deposited subsequent to the burial of the sludge.

The 30 background surface samples (Table 3) display similar results to the surface samples taken from the area where the sludge was buried. A total of 47 Ascaris ova were recovered from 600 g of sludge, of which 47 were dead and 10 necrotic. These results are not significantly different from the

Ascaris incidence detected in the surface soil where the sludge was buried. This indicates that the Ascaris that is observed on the surface where the sludge was buried is representative of the area in general, and is therefore not necessarily the result of the sludge burial operations.

Table 1 Results for sludge samples
(samples A, B and C taken from trenches 2, 4, 6, 10, 12, 14, 17, 19, 21)

VISUAL - Macroscopic Description of Samples	SAMPLE NUMBER (10g)	*ASCARIS*						*Tt*	*TAENIA*
		UN-DEVELOPED	MOTILE	IMMOTILE	NECROTIC	DEAD	INFERTILE		
DRY, LUMPY DAMP CLUMPS	2A	0	0	0	30	66	0	148	0
DRY, SANDY	4A	0	0	0	0	7	0	41	0
WET	6A	0	0	0	10	104	0	5	0
DRY,SANDY,MOIST CLUMPS	8A	0	0	0	0	3	0	0	21
SANDY, CLUMPY	10A	1	1	0	1	18	0	102	1
DAMP, LOTS OF ROOTS ,BROKEN GLASS	12A	0	0	0	0	10	0	30	0
MOIST, SANDY, FEW CLUMPS, BROKEN CHINA	14A	0	0	0	0	5	0	21	0
MOIST, SANDY, FEW CLUMPS	17A	0	0	0	0	3	0	2	0
MOIST, CLUMPY, BROKEN GLASS	19A	0	0	0	45	105	0	49	2
MOIST, SANDY, FEW CLUMPS	21A	0	0	0	1	4	0	176	0
MOIST, SANDY, ROOTS	2B	0	0	1	12	48	0	27	0
MOIST, LUMPY	4B	0	0	17	12	218	0	262	0
MOIST, LUMPY	6B	0	0	0	48	572	0	657	9
MOIST, LUMPY, ROOTS	8B	0	0	4	4	59	0	7	0
MOIST, LUMPY	10B	1	0	1	0	0	0	0	2
MOIST, CLEAN	12B	0	0	0	5	133	0	19	2
MOIST, CLEAN, LUMPS	14B	0	0	0	0	5	2	0	0
MOIST, CLUMPY	17B	5	0	0	1	1	1	3	2
MOIST, LUMPS, ROOTS	19B	2	0	5	4	6	1	0	0
WET, ROOTS	21B	5	0	3	0	1	0	2	1
MOIST, CLEAN, FEW ROOTS	2 C	0	0	0	1	2	0	1	0
VERY DAMP, DREADLOCKS	4 C	1	0	0	1	1	0	1	0
VERY DAMP, CLEANISH	6 C	0	0	0	1	4	0	1	0
MOIST, CLEAN, FEW LUMPS	8 C	0	0	0	0	7	0	9	0
DAMP, CLEAN, GLASS	10 C	1	0	0	0	10	0	2	4
WET,CLEAN	12 C	0	0	0	0	0	0	0	0
VERY DAMP, CLEAN	14 C	0	0	0	0	0	0	0	0
WET, CLEAN	17 C	0	0	0	0	0	0	0	0
WET, CLEAN	19 C	0	0	0	0	1	0	0	0
VERY WET, HARD LUMPS	21 C	0	0	0	0	4	1	0	0
TOTALS		16	1	31	176	1397	5	1565	44
TOTAL ASCARIS (all conditions)		1626							

Table 2 Results for surface samples above trenches

VISUAL - Macroscopic Description of Samples	SAMPLE NUMBER (20g)	*ASCARIS*						*Tt*	*TAENIA*
		UN-DEVELOPED	MOTILE	IMMOTILE	NECROTIC	DEAD	INFERTILE		
FINE DRY SAND ,FINE ROOTS, LUMPS	5D	0	0	0	2	14	0	2	0
FINE DRY SAND,FINE ROOTS,SMALL LUMPS	7D	0	0	0	0	5	0	0	0
FINE DRY SAND, FEW ROOTS, FEW LUMPS	9D	0	0	0	0	0	0	0	0
FINE DRY SAND	11D	0	0	0	0	2	0	0	0
DRY LUMPY SAND ,FINE ROOTS	13D	0	0	0	0	6	0	0	0
FINE DRY LUMPY SAND, FINE ROOTS	15D	0	0	0	0	3	0	0	1
DRY LUMPY SAND,FINE ROOTS	18D	0	0	0	0	9	0	0	0
DRY LUMPY SAND, FINE ROOTS	20D	0	0	0	0	1	0	0	0
FINE DAMP SAND, FEW ROOTS, FEW SMALL LUMPS	1E	0	0	0	0	1	0	0	0
FINE DAMP SAND, FEW ROOTS	3E	0	0	0	1	5	0	0	0
FINE DAMP SAND, FEW ROOTS	5E	0	0	0	0	1	0	0	0
FINE DAMP SAND,FEW ROOTS, SOME BIG CLUMPS	7E	0	0	0	0	6	0	0	0
FINE DAMP SAND, FEW FINE ROOTS, FEW BIG CLUMPS	9E	0	0	0	0	3	0	0	0
FINE DAMP SAND, FINE ROOTS,CLUMPS	11E	0	0	0	0	0	0	0	0
FINE DAMP SAND, FINE ROOTS	13E	0	0	0	0	0	0	0	0
FINE DAMP SAND, FINE ROOTS, SMALL CLUMPS	15E	0	0	0	0	2	0	0	0
FINE DAMP SAND, ROOTS, CLUMPS	18E	0	0	0	0	12	0	0	0
FINE DAMP SAND, ROOTS, CLUMPS	20E	0	0	0	0	1	0	0	0
FINE DAMP SAND,ROOTS,CLUMPS	1F	0	0	0	0	1	0	2	2
FINE DAMP SAND, SOME ROOTS, CLUMPS	3F	0	0	0	0	0	0	0	0
FINE DAMP SAND, STICKS, MANY CLUMPS	5F	0	0	0	0	0	0	0	0
FINE DAMP SAND, STICKS, MANY CLUMPS	7F	0	0	0	0	0	0	0	0
FINE DAMP SAND, FEW ROOTS, MANY CLUMPS	9F	0	0	0	0	0	0	0	0
FINE DRY SAND, MANY ROOTS, MANY CLUMPS, STICKS	11F	0	0	0	0	0	0	0	0
FINE DRY SAND, MANY ROOTS, MANY CLUMPS, STICKS, DE	13F	0	0	0	0	0	0	0	0
FINE, DAMP SAND, ROOTS, CLUMPS,	15F	0	0	0	0	0	0	0	752 POSSIBLY VIABLE
FINE DAMP SAND, FEW ROOTS, STICKS, CLUMPS	18F	0	0	0	0	0	0	0	0
FINE DRY - DAMP SAND, ROOTS, CLUMPS, SOME STICKS	20F	0	0	0	0	0	0	1	1 POSSIBLY VIABLE
TOTALS		0	0	0	3	72	0	5	

Table 3 Results for background surface samples

VISUAL - Macroscopic Description of Samples	SAMPLE NUMBER (20g)	*ASCARIS*						*Tt*	*TAENIA*
		UN-DEVELOPED	MOTILE	IMMOTILE	NECROTIC	DEAD	INFERTILE		
FINE DAMP, ROOTS CLUMPS	1G	0	0	0	0	0	0	0	0
FINE DAMP SAND, MANY ROOTS, CLUMPS,SHOOTS, DEBR	2G	0	0	0	0	0	0	0	0
FINE DAMP SAND, MANY ROOTS, SHOOTS ,STICKS, CLUMP	3G	0	0	0	0	0	0	0	0
FINE DAMP SAND, ROOTS, MANY CLUMPS	4G	0	0	0	0	0	0	0	0
FINE DAMP SAND, MANY ROOTS, CLUMPS	5G	0	0	0	0	0	0	0	0
FINE DAMP SAND, MANY ROOTS, MANY LARGE CLUMPS	6G	0	0	0	0	0	0	0	0
FINE DRY-DAMP SAND, MANY ROOTS,STICKS, MANY LARG	7G	0	0	0	0	0	0	0	0
FINE DAMP SAND, ROOTS, SHOOTS, MANY CLUMPS	8G	0	0	0	0	3	0	3	0
FINE DRY-DAMP SAND, ROOTS, MANY CLUMPS	9G	0	0	0	0	3	0	0	0
FINE DAMP SAND, ROOTS, SHOOTS, CLUMPS	10G	0	0	0	0	3	0	0	0
FINE DRY-DAMP SAND, ROOTS, MANY CLUMPS	11G	0	0	0	0	1	0	0	0
FINE DRY SAND, ROOTS, MANY CLUMPS	12G	0	0	0	1	12	0	1	0
FINE DRY SAND, MANY ROOTS, MANY CLUMPS,DEBRIS	13G	0	0	0	0	0	0	0	0
FINE DAMP SAND, ROOTS, CLUMPS	14G	0	0	0	0	3	0	0	0
FINE-COARSE, DRY-DAMP SAND, MANY CLUMPS	15G	0	0	0	0	11	0	2	0
FINE DAMP SAND, ROOTS, MANY CLUMPS	16G	0	0	0	1	0	0	0	1
FINE DAMP SAND, ROOTS, MANY CLUMPS	17G	0	0	0	2	0	0	1	1
FINE DRY SAND, ROOTS, MANY CLUMPS,DEBRIS	18G	0	0	0	0	1	0	0	0
FINE-COARSE DRY SAND, ROOTS, MANY CLUMPS, DEBRIS	19G	0	0	0	0	0	0	0	0
FINE-COARSE DRY SAND,MANY CLUMPS, MANY ROOTS, STICKS, STONES ,DEBRIS	20G	0	0	0	0	1	0	0	0
FINE-COARSE DRY SAND, COPPERY COLOUR, MANY ROOTS, LARGE CLUMPS, STICKS, STONES, DEBRIS	21G	0	0	0	0	0	0	0	0
FINE-COARSE DRY SAND, MANY ROOTS, LARGE CLUMPS, STICKS, STONES, DEBRIS	22G	0	0	0	0	0	0	0	0
FINE DRY SAND,MANY CLUMPS, MANY ROOTS, DEBRIS	23G	0	0	0	0	0	0	1	0
FINE DAMP SAND, MANY CLUMPS, ROOTS, SHOOTS	24G	0	0	0	0	1	0	0	1
FINE DAMP SAND, MANY CLUMPS, ROOTS, SHOOTS	25G	0	0	0	0	1	0	0	0
FINE DAMP SAND, CLUMPS,MANY ROOTS	26G	0	0	0	6	7	0	0	0
FINE DRY-DAMP SAND,MANY CLUMPS, ROOTS	27G	0	0	0	0	0	0	0	0
FINE DRY SAND, MANY CLUMPS, ROOTS	28G	0	0	0	0	0	0	0	0
FINE DRY-DAMP SAND, CLUMPS, ROOTS	29G	0	0	0	0	0	0	0	0
FINE DRY SAND, ROOTS, MANY CLUMPS	30G	0	0	0	0	0	0	0	0
TOTALS		0	0	0	10	47	0	8	3

3. SAPPI SITE

Further pathogen testing was done at the Sappi site in March 2013. Twenty soil samples were taken from the surface or near the surface within the experimental site (see Transect F in Figure 1 below) and twenty from above the site (G1 to G10) and alongside the site (G11 to G20). The purpose was to check to what extent the intervention of burying sludge on the experimental site had increased the presence of helminth ova relative to the surrounding background level.

Figure 2 Location of Transects F and G at Sappi Experimental Site

Table 4 below shows the number of ova detected in the 20 samples taken from the F transect.

Note that all *Taenia* and *Trichuris* ova were dead, whereas (as before) the classification of the *Ascaris* ova were split according as follows: undeveloped, motile, immotile, infertile, necrotic or dead.

Table 4 Helminth counts in soil samples taken from near surface (Transect F) within experimental site

VISUAL - Macroscopic Description of Samples	SAMPLE NUMBER (20g)	*ASCARIS*						*Tt*	*TAENIA*
		UNDEVELOPED	MOTILE	IMMOTILE	NECROTIC	DEAD	INFERTILE		
SMALL STONES, ROOTS, STICKS,DAMP	F1	0	0	0	0	0	0	0	0
DAMP, ROOTS, CLUMPS	F2	0	0	0	0	0	0	1	0
DAMP, ROOTS, CLUMPS	F3	0	0	0	0	3	0	0	0
DAMP, ROOTS, CLUMPS	F4	0	0	0	0	0	0	0	0
DAMP, CLAY LIKE CLUMPS	F5	0	0	1	0	3	0	0	0
DAMP, LARGE CLUMPS	F6	0	0	0	0	0	0	0	1
DAMP, LARGE CLUMPS	F7	0	0	0	0	3	0	0	0
DAMP, LARGE CLUMPS	F8	0	0	0	0	1	0	0	0
DAMP, LARGE CLUMPS	F9	0	0	0	0	0	0	1	0
DAMP, LARGE CLUMPS	F10	0	0	0	0	2	0	0	0
DAMP, CLUMPY	F11	0	0	0	0	0	0	0	0
DRYISH - DAMP, CLUMPY	F12	0	0	0	0	3	0	0	0
DRYISH -DAMP, LARGE CLUMPS	F13	0	0	1	0	0	0	0	0
DRYISH-SANDY,SMALL CLUMPS	F14	0	0	0	2	1	0	0	3
MOIST, LARGE CLUMPS	F15	0	2	2	3	12	0	1	23 POSSIBLY VIABLE
DAMP-DRY, CLUMPS	F16	0	0	0	2	0	0	0	1 POSSIBLY VIABLE
DAMP-DRY, LARGE CLUMPS	F17	0	0	0	0	0	0	0	0
DAMP, LARGE CLUMPS	F18	0	0	1	2	2	0	0	2
DRY - DAMP, FEW CLUMPS, MOULDY	F19	0	0	0	0	0	0	0	0
DAMP, CLUMPY	F20	0	4	2	2	3	0	0	0
TOTALS			**6**	**7**	**11**	**33**	**0**	**3**	**30**

The total count of ova from Transect F came to 90 of which 57 were *Ascaris*, 3 *Trichuris* and 30 *Taenia*. It is notable that 23 or 77% of the *Taenia* came from just one sample. Six of the *Ascaris* were motile, 7 immotile, 11 were necrotic and 33 were dead.

The results from background transects G1-G10 (above the site) and G11 to G20 (next to the site) are shown in Table 5.

Table 5 Helminth counts in soil samples taken from near surface (Transect G) outside of experimental site

VISUAL - Macroscopic Description of Samples	SAMPLE NUMBER (20g)	*ASCARIS*						*Tt*	*TAENIA*
		UNDEVELOPED	MOTILE	IMMOTILE	NECROTIC	DEAD	INFERTILE		
DAMP, FEW FINE ROOTS	G1	0	0	0	0	0	0	0	0
DAMP, FEW FINE ROOTS	G2	0	0	8	2	4	0	0	3
DAMP, FEW FINE ROOTS, CLUMPS	G3	0	0	0	2	3	0	0	0
DRY-DAMP, FINE ROOTS	G4	0	0	0	0	2	0	0	0
DRYISH	G5	0	0	0	0	0	0	0	0
DRYISH, FINE ROOTS, GROWING	G6	0	0	0	2	1	0	0	0
DRYISH, FINE ROOTS,GROWING,REDDISH CLAY LIKE	G7	0	0	0	0	0	0	0	0
DAMPISH, FINE ROOTS, GROWING	G8	0	0	0	0	0	0	0	0
DRY-DAMP, FINE ROOTS	G9	0	0	0	0	0	0	0	0
DAMP, FINE ROOTS GROWING, LARGE CLUMPS	G10	0	0	0	0	2	0	0	0
MOIST, SOLID PIECE	G11	0	0	0	0	0	0	0	0
DRYISH-DAMP, MANY FINE ROOTS	G12	0	0	0	1	3	0	0	0
DAMP, FEW FINE ROOTS, LARGE CLUMPS	G13	0	0	0	0	1	0	0	0
DAMP, SOLID PIECE, FINE ROOTS	G14	0	0	0	0	0	0	0	0
DRY-DAMP,FINE ROOTS, SOLID	G15	0	0	0	0	0	0	0	0
LARGE CLUMPS, DAMP,FINE ROOTS, GROWING	G16	0	0	0	0	0	0	0	0
DAMP, SOLID PIECE, FEW FINE ROOTS	G17	0	0	0	0	0	0	0	0
DAMP, ROOTS, MOSTLY SOLID PIECE	G18	0	0	0	0	0	0	0	0
DAMP, CLUMPS, TWIGS	G19	0	0	0	0	0	0	0	0
DAMP, FINE ROOTS, MOSTLY SOLID PIECE	G20	0	0	0	0	0	0	0	0
TOTALS				**0**	**5**	**12**	**0**	**0**	**0**

The total count of ova from Transect G came to 17 all of which 17 were *Ascaris*. Five of the *Ascaris* were necrotic and 12 were dead.

Transect F had five times the number of ova relative to Transect G. Although the numbers are small (for example in fresh VIP sludge in Durban researchers typically find up to 1000 Ascaris ova per gram of faecal sludge) the difference between F and G is nevertheless noticeable.

APPENDIX F

Changes in Sludge Characterization

1. INTRODUCTION

During the first 30 months of this experimental work (January 2009 to June 2011) the following changes in the sludge were monitored at the Umlazi site: COD content; volatile solids and moisture content.

In January 2013 a further 30 samples were taken and analysed to ascertain to what extent the sludge samples had changed after a further 18 months.

2. RESULTS

In January 2013 thirty sludge samples were dug up from the Umlazi site and sent to the PRG lab for analysis.

The results of the analyses are shown in Figures 1 to 8 below.

2.1 CHANGES IN COD

The COD of the pit sludge at the time of burial (i.e. soon after it had been removed from the pit) ranged from 0.1 g to 0.54 g COD / g dry sample, with a median of 0.25 g. The wide range of values is attributable to the heterogeneous nature of VIP sludge, including fresh both faecal material and faecal material which will have been in the pit for several years. With the progression of time, as the fresher sludge decomposes, the median value appears to stabilize around 0.11 g COD. The variation in the results from sampling period to sampling period in Figure 1 is again attributable to the heterogeneous nature of the sludge.

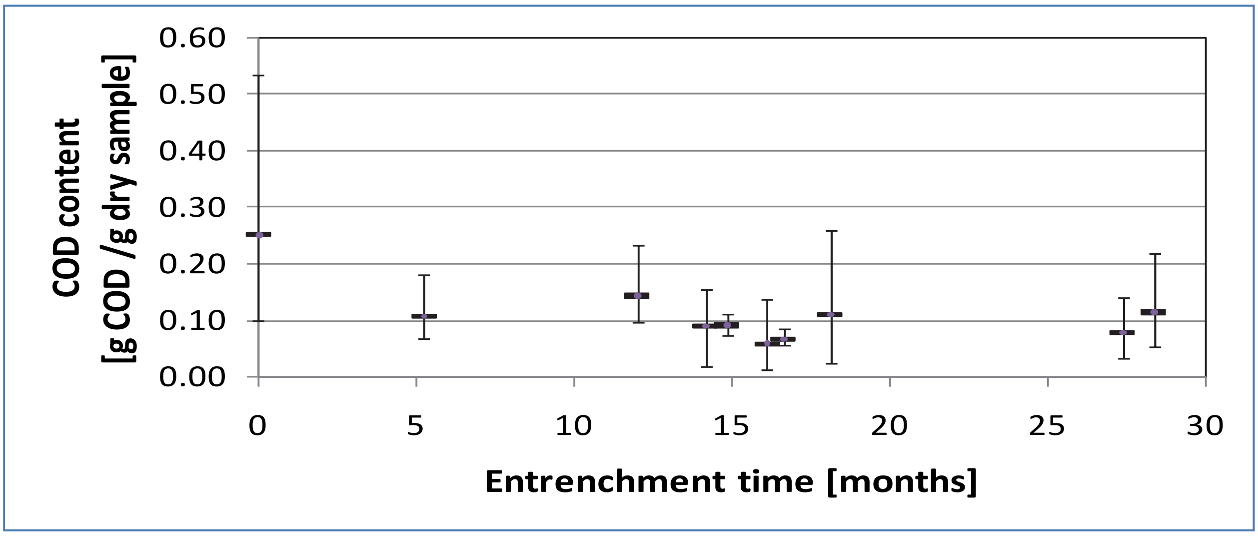


Figure 1 Change in sludge COD over the first 30 months

After a further eighteen months the COD of the 30 samples was found to vary from 0.006 to 0.263 g COD / g dry sample (Figure 2). The median value was 0.047 g (down from 0.11 at 30 months). Again the variation in the COD is wide. The average value was 0.097 g/g dry sample. It seems that the rate of change in the sludge is now very slow.

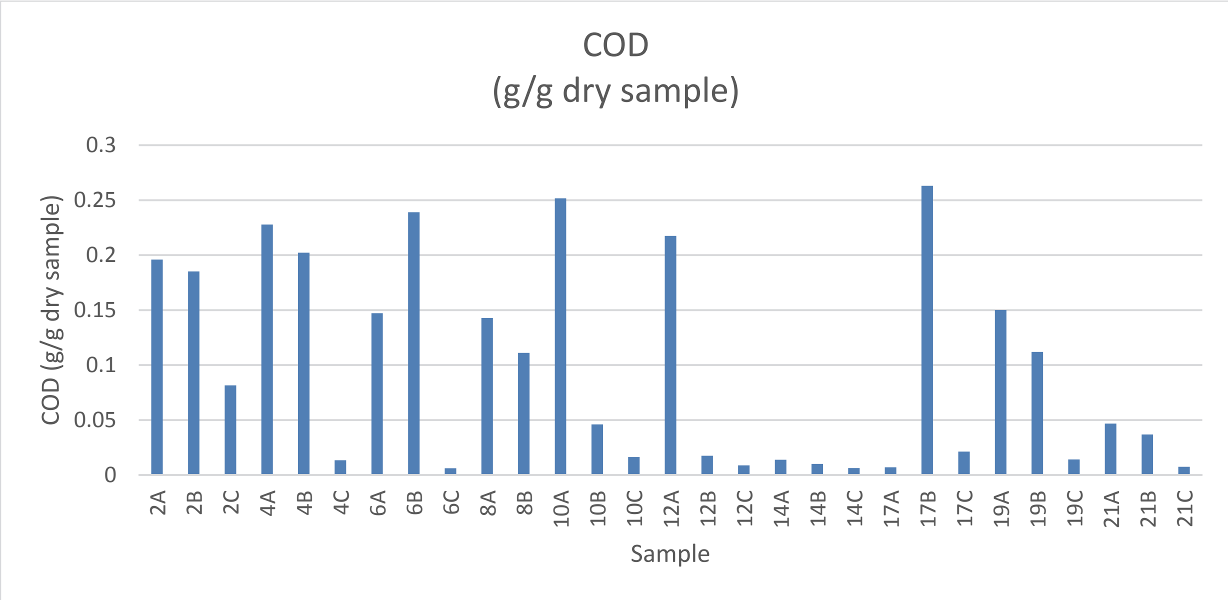


Figure 2 Variation in sludge COD after 48 months

2.2 CHANGES IN VOLATILE SOLIDS

The volatile solids content of the pit sludge (i.e. the organic portion, as opposed to grit, etc.) at the time of burial (i.e. soon after it had been removed from the pit) ranged from 20 to 85% of the dry sample mass, with a median of 60% (Figure 3). The wide range of values is attributable to the heterogeneous nature of VIP sludge, including fresh both faecal material and faecal material which will have been in the pit for several years. By 30 months the median volatile solids appeared to have stabilised at 25%, although the range (from 0 to 50% was still wide).

After a further 18 months the median volatile solids had decreased to 1.9%, with an average of 3.7% (Figure 4). With the exception of one notable outlier, the variation is all from 0 to 10%, which is a narrower band than was the case at 30 months.

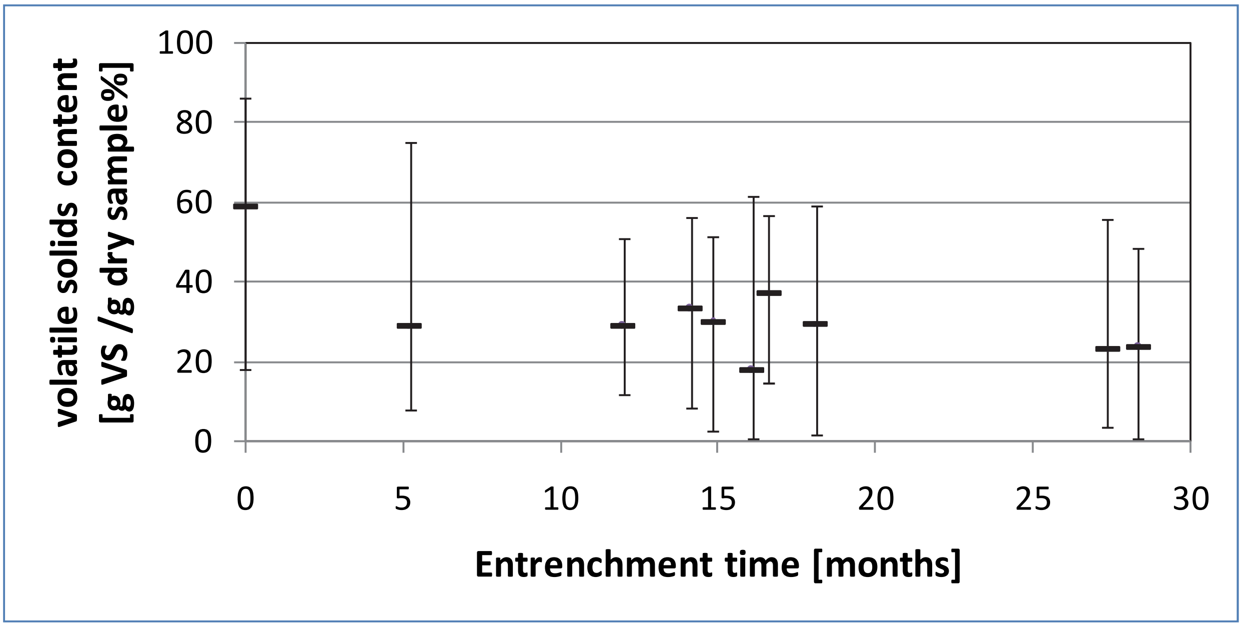


Figure 3 Change in sludge volatile solids over the first 30 months

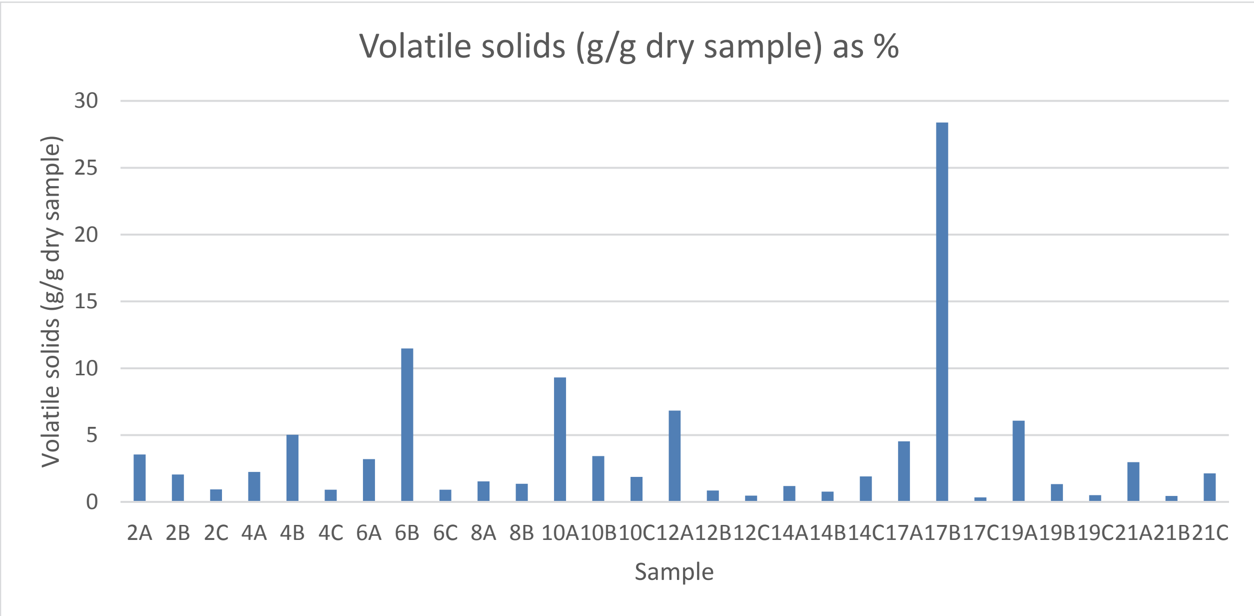


Figure 4 Variation in sludge Volatile Solids after 48 months

2.3 CHANGES IN MOISTURE CONTENT

The moisture content of the pit sludge at the time of burial (i.e. soon after it had been removed from the pit) ranged from 60 to 90% g moisture / g wet sample, with a median of 75% (Figure 5). The wide range of values is attributable to the heterogeneous nature of VIP sludge, including fresh both faecal material and faecal material which will have been in the pit for several years. With the progression of time, as the fresher sludge decomposes, the median value appears to stabilize around 35%.

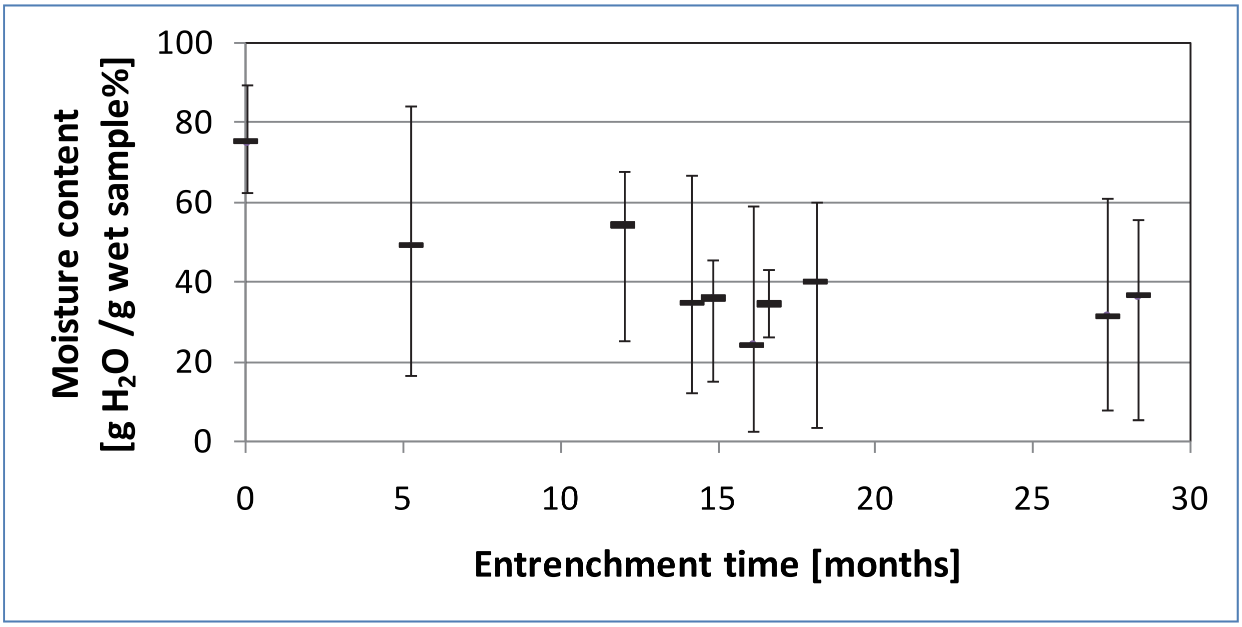


Figure 5 Change in sludge moisture content over the first 30 months

After a further 18 months the median moisture content has decreased to 13% with an average of 14%. Although there is still considerable variability in the sludge moisture content, the range of variation has narrowed to 5 to 30%.

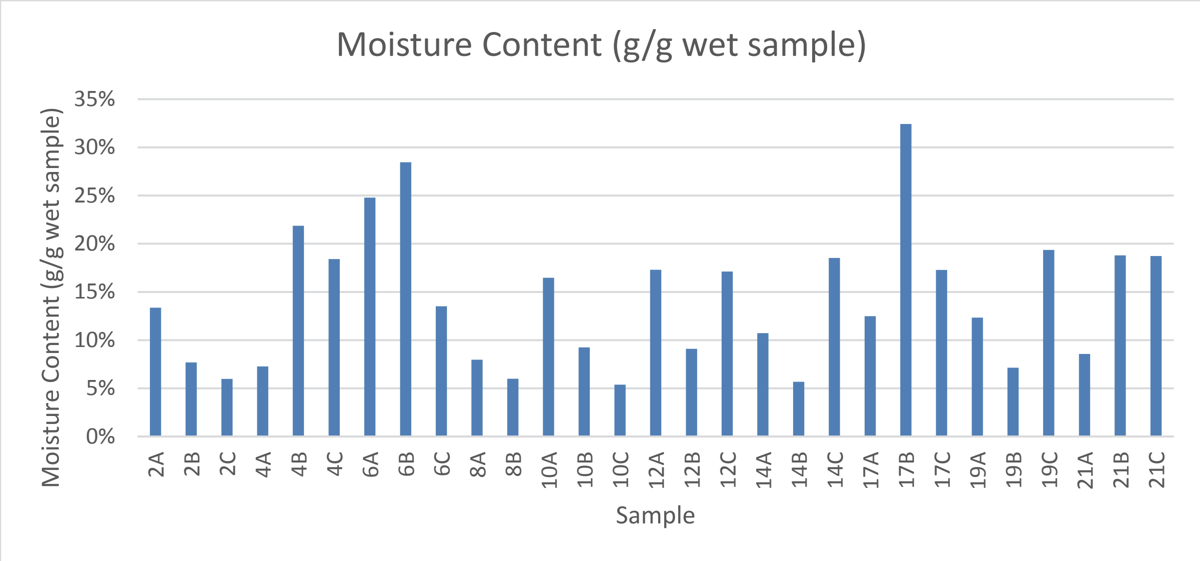


Figure 6 Variation in sludge Moisture Content after 48 months

2.4 NITRATE AND PHOSPHATE CONTENT

The total nitrogen content of the sludge samples was not monitored during the first 30 months of this research. However, from published results it is expected that the total nitrogen in the sludge at the time of burial would have been in the order of 5%. After 48 months the median nitrogen (measured as TKN) has reduced to 0.31%, with an average of 0.37% (Figure 7). After four years then more than 90% of the nitrogen that has been buried in the soil has been coverted from an organic form to an inorganic form. It has either leached out of the soil as nitrate, volatilised as nitrogen, or been taken up by the plant matter.

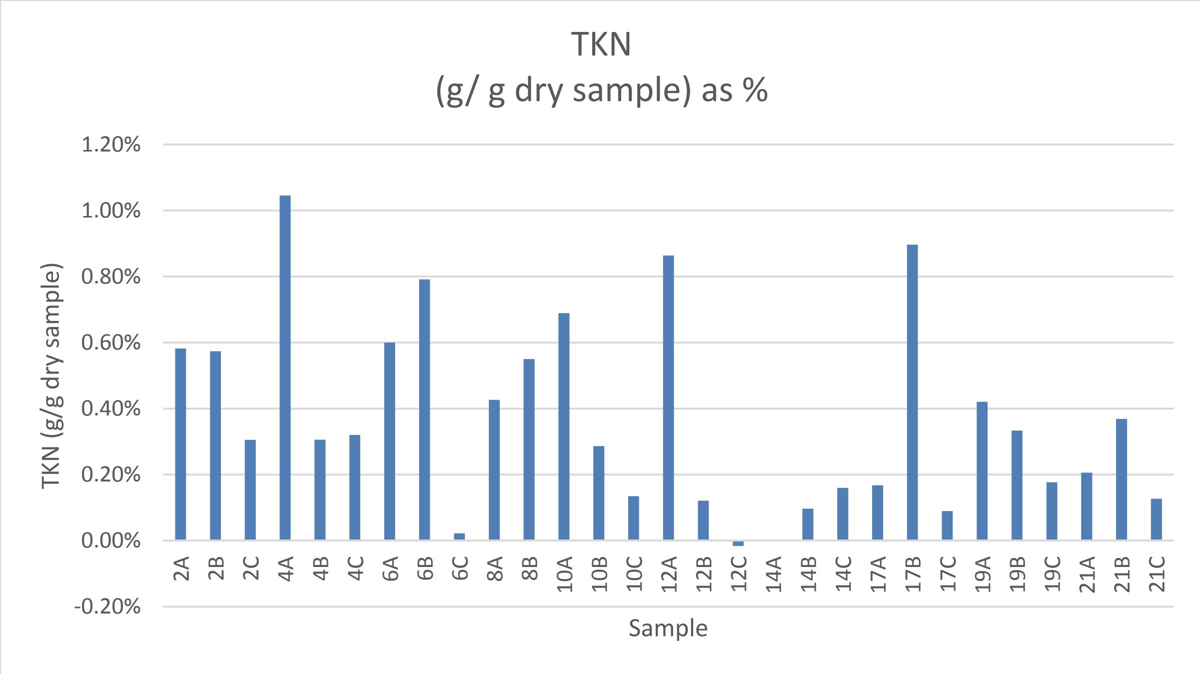


Figure 7 Variation in sludge TKN after 48 months (inorganic N was zero)

Very little can be concluded from the results of the phosphate tests. Only 5 of the 30 samples tested positive for any phosphate (Figure 8). The range observed is from 0.2% to 1.2%.

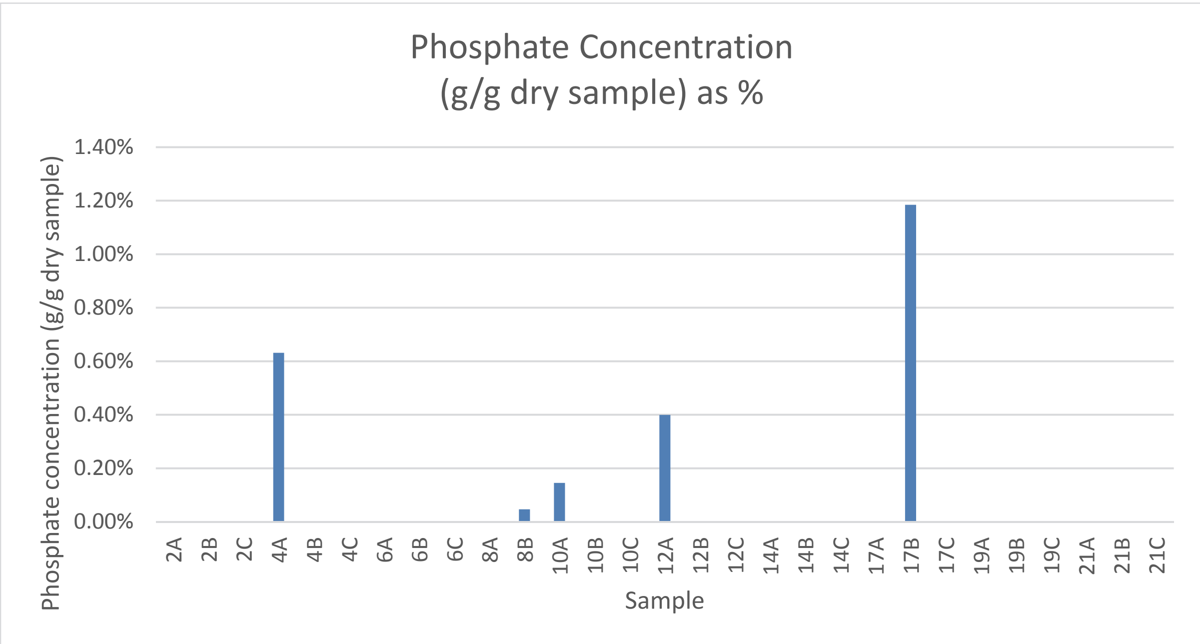


Figure 8 Variation in sludge Phosphate after 48 months