Sustainable approaches to sludge disposal for the Darvill Wastewater Treatment Works (WWTW).

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DECLARATION

I, Nkosingiphile Emmanuel Cele, declare that this research report is my own unaided work. It is being submitted in partial fulfilment of the requirements for the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

N.E Cele

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(Signature of Candidate)

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ABSTRACT

The disposal of sludge produced during wastewater treatment, by means of land application, can have negative impact on the receiving environment if not properly monitored. For example, the use of sludge containing excessive amounts of heavy metal, as organic fertilizer, has potential to lead to soil and water pollution and can interfere with plant growth and yield. As a result, the presence of excessive amounts of heavy metals in the sludge may limit the potential use of sludge for agricultural purposes. This study aims to assess the sludge disposal method currently employed at Darvill Wastewater Treatment Works (WWTW) against the future design flow, to establish whether the current sludge disposal method will be sufficient for the new treatment capacity in terms of discharge limits set for sludge disposal by land application. In this study a model which can be used to predict the impact of increasing sludge application on the receiving environment is developed. While the site of the project is the Darvill WWTW, located in Pietermaritzburg in the province of KwaZulu-Natal, knowledge gained from this exercise can be useful to engineers and/or researchers trying to determine the lifespan of sludge disposal lands, using current soil conditions and the anticipated quality of sludge as inputs, in other areas. For the purpose of this model it has been assumed that the disposal of the treated sludge is done on a daily basis and that the sludge is evenly distributed across the sludge disposal land. The soil moisture content and soil bulk density were used to determine the amounts of solutes retained at various depths, with the amount of solutes retained decreasing with increasing soil depth. The concentration of Cd, Cr, Cu and Zn for the top 200mm of soil increases significantly due to the relatively low soil bulk density and high soil moisture content after 1 year of discharge with no removal of grass. The concentration of As, Cr, Pb and Zn exceed the maximum permissible level (MPL) when one models the disposal of sludge over a 10 year period with no removal of grass at the Darvill sludge land. The simple model presented in this research report will enable engineers and/or scientists to predict the concentrations of heavy metals to be expected in the soil based on the mass of solute retained. This approach enables engineers and/or scientists to be able to adopt mitigation measures to reduce the impact of non-compliance with the discharge limits as set out in the guidelines for utilisation and disposal of wastewater sludge.

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LIST OF ABBREVIATIONS

As	Arsenic
k_b	Backward reaction rate coefficient
Cd	Cadmium
Cr	Chromium
Cu	Copper
DAF	Dissolved Air Flotation
DWS	Department of Water and Sanitation
k_d	Distribution coefficient
k_f	Forward reaction rate coefficient
HCL	Hydrogen Chloride
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometer
ICP-MS	Inductively Coupled Plasma Mass Spectrometer
Pb	Lead
MPL	Maximum Permissible Level
Hg	Mercury
Ni	Nickel
NO_3	Nitrate
HNO_3	Nitric acid
PST	Primary Settling Tank
PAR	Permissible Application Rate
BD	Soil Bulk Density
TLB	Tractor-Loader-Backhoe
TMT	Total Maximum Threshold
UW	Umgeni Water
WWTW	Wastewater Treatment Work
Zn	Zinc

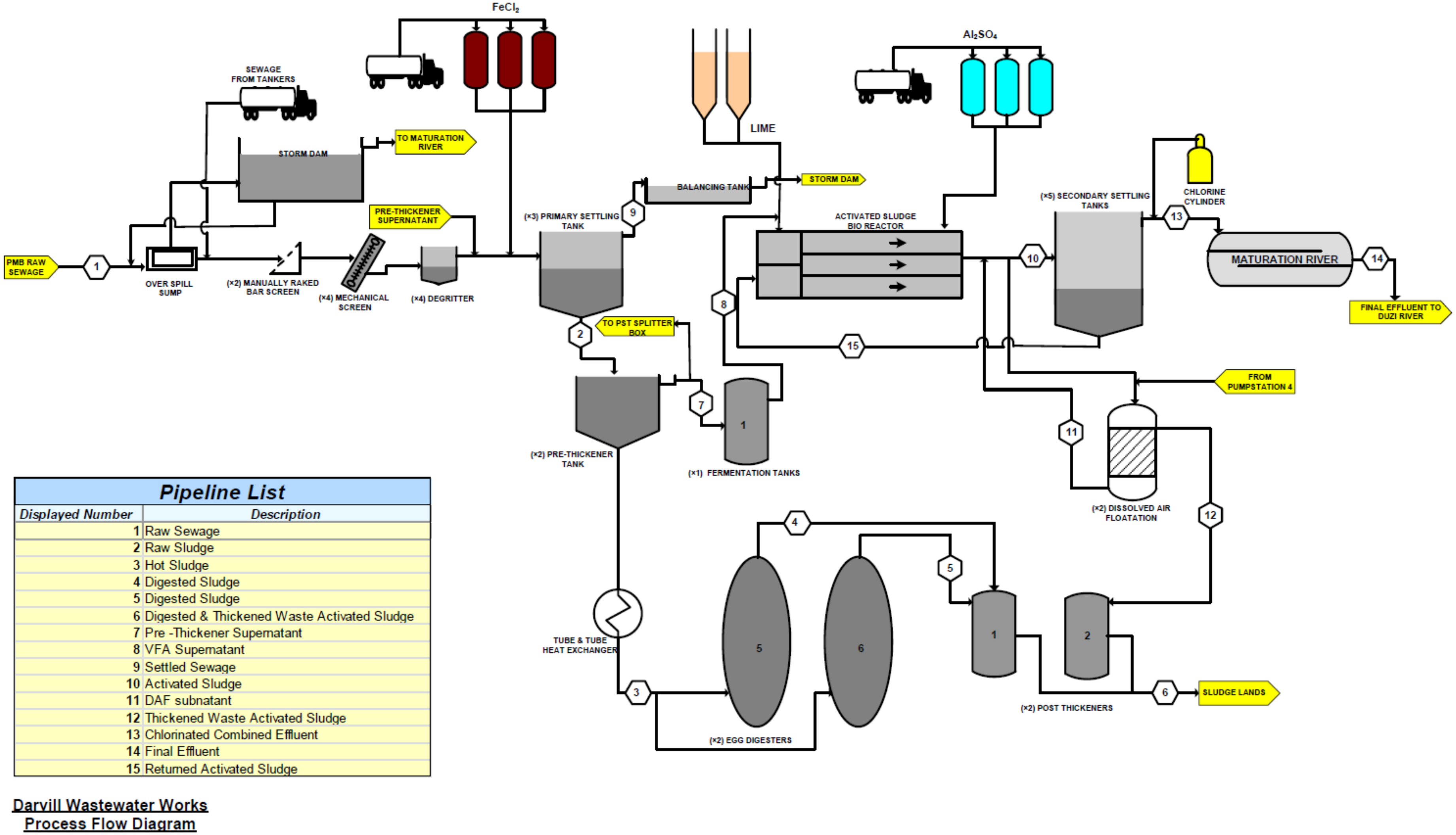
1. INTRODUCTION

1.1 Introduction

The Darvill Wastewater Treatment Works (WWTW) is located in Pietermaritzburg. This plant is one of only two WWTW responsible for treating wastewater generated across the Msunduzi Municipality. The current biological treatment capacity of Darvill WWTW is 65Ml/d, with the current dry weather flow being 70Ml/d and the wet weather flow being 90Ml/d. The sludge generated at Darvill WWTW is currently being irrigated onto land, a system which is functioning quite adequately (Westgate, 2014).

Darvill WWTW is currently undergoing an upgrade from 65Ml/d to 120Ml/d to cater for both current and future flows (Westgate, 2014). With the increase in treatment capacity, the volume of sludge, from wastewater treatment, will also increase, which leads to the need to assess the current sludge disposal method against the new treatment capacity.

At a WWTW solids needing treatment may come from such operations as screening, grit removal, primary and secondary sedimentation/settling, air flotation, as well as biological treatment amongst others (Burton et al., 2003). The primary sources of wastewater solids at the Darvill WWTW are the primary settling tanks and dissolved air flotation tank.



Pipeline List

Displayed Number	Description
1	Raw Sewage
2	Raw Sludge
3	Hot Sludge
4	Digested Sludge
5	Digested Sludge
6	Digested & Thickened Waste Activated Sludge
7	Pre -Thickener Supernatant
8	VFA Supernatant
9	Settled Sewage
10	Activated Sludge
11	DAF subnatant
12	Thickened Waste Activated Sludge
13	Chlorinated Combined Effluent
14	Final Effluent
15	Returned Activated Sludge

Figure 1.1: Darvill WWTW Process Flow Diagram (Mbhele, 2015).

During the process of wastewater treatment, at the Darvill WWTW, the solids removed from the primary settling tank (PST) are pumped to the pre-thickener, where further separation of the liquid and solid components takes place. The solids are then pumped into an anaerobic digester where they are stabilized.

The activated sludge from the reactor basin is taken into the dissolved air flotation (DAF) tank where the suspended solids that remain are removed from the wastewater stream. The solids from both the DAF tank and the anaerobic digester are taken to the post thickeners; from the post thickeners the sludge is then pumped to the Darvill sludge land where it is sprayed onto land and subsequently removed in the form of instant lawn (see figure 1.1). The harvested grass is sold commercially for uses such as road verging, grassing of sports fields, and landscaping by property developers or individuals.

With the planned expansion of the Darvill WWTW there is a need to investigate if the current sludge disposal method is adequate to meet the discharge standards as set by the Department of Water and Sanitation (DWS) for the new treatment capacity (Herselman & Snyman, 2006).

The characteristics of solids from wastewater treatment are of great importance in selecting the most effective treatment process as well as the most appropriate beneficial use of the treated solids above all else. For example, when considering land application of wastewater treatment solids one must look at the levels of organic matter, nutrients, pathogens, metals, and toxic compounds (Snyman, 2006).

Special attention is given to these constituents due to the negative impacts they may have on the receiving environment, for example:

- The disposal of treated wastewater with high concentrations of organic matter may result in the depletion of oxygen, and, the development of septic conditions in receiving waters;
- The disposal of solids containing high nutrient concentrations onto land may result in the contamination of groundwater, and the disposal of same into aquatic environments may result in eutrophication of receiving waters. It should be noted that for the purpose of this research report, when reference is made to groundwater it is shallow groundwater and not deep groundwater.

- When treated wastewater containing pathogens such as bacteria, viruses, protozoa and helminths is used for watering vegetable gardens this would leave the people who consume said vegetables susceptible to infections.
- The disposal of solids containing high levels of heavy metals is a risk to human and animal life as well as environmental health (Herselman & Snyman, 2006). Negative impacts on plant growth and health include the decrease of seed germination and lipid content (linked to the presence of Cd and Ni), decrease in plant growth and enzyme activity (linked to the presence of Cr), the hindrance of photosynthesis (linked to the presence of Cu and Hg) (Achmad et al., 2017; Akpor et al., 2014; Tiwari et al., 2013).

1.2 Background

Amongst circumstances that can result in the need to increase the treatment capacity of the WWTW are (Le Roux et al., 2005):

- WWTW operating at/or, near capacity.
- Population and/or economic growth within the area serviced by a WWTW.
- Expansion in terms of the number of areas serviced by a treatment works.
- Treatment works needing upgrade in order to meet new discharge limits.
- The need to replace existing processes with newer and more efficient processes.

Upgrading of WWTW is not only achieved through the conventional method of plant expansion, but it can also be achieved by performing regular maintenance as well as the identification and subsequent removal of any potential bottleneck which may have an impact on the treatment capacity of the works (Buttz & Diagger, 1998). The need to increase the treatment capacity of WWTW as a result of one or more circumstances as mentioned above is particularly applicable to South Africa as a developing country. Utility managers are faced with the challenge of aging infrastructure, dealing with increased volumes of wastewater due to housing developments and water infrastructure developments. In most cases, the conventional works capacity expansion is adopted to deal with the factors mentioned before (Le Roux et al., 2005).

Upgrading of existing WWTW requires application for a water use license for the discharge of the final effluent, which generally means the upgraded treatment works is to comply with more stringent discharge limits as set by the Department of Water and Sanitation (Buttz & Diagger, 1998).

1.3 Objectives

The objectives of this study are to:

- Assess the sludge disposal method currently employed at Darvill WWTW against current design flow.
- Assess the sludge disposal method currently employed at Darvill against future design flow, to establish whether the current sludge disposal method will be sufficient for the new treatment capacity, in terms of discharge limits set for sludge disposal by land application.
- Assess the fate of heavy metals and nutrients at the Darvill WWTW, including the sludge land.
- Provide a recommendation on the amount of sludge that may be disposed of by land application.

1.4 Motivation

This study produces a blueprint for assessing the sustainability of sludge disposal through irrigation for conventional activated sludge WWTW. The results from this study will help enable engineers and/or scientists to assess whether WWTW undergoing major upgrades can be able to dispose sludge through irrigation on existing sludge lands.

Assessing the lifespan of the sludge lands will help inform when it is necessary to start investigating alternative feasible sludge disposal methods. This will in turn ensure continuous compliance with the disposal limits as set by the Department of Water and Sanitation, and by doing so prevent environmental harm.

1.5 Structure of research report

The research report presented is structured in the following manner:

Chapter 2, *Literature review*, presents a review of literature on the treatment and disposal of wastewater and sludge.

Chapter 3 presents the methodology adopted for the study conducted. A description of the field tests conducted and laboratory procedure followed is discussed in detail.

Chapter 4, *Results and Discussion,* contains a summary of results obtained. The limitations and assumptions made are presented in this chapter. Chapter 4 is concluded by discussing the general observations.

Chapter 5 contains the conclusions made and the potential use of the research.

2. LITERATURE REVIEW

Wastewater is treated so as to protect public health and the environment (Burton et al., 2003; Andreoli et al., 2007; Sikhakhane, 2001). During the wastewater treatment process, the solids and biosolids that are recovered require further treatment prior to disposal in order to protect public health and the environment (ICE, 1985).

The term biosolids mentioned above is used to make reference to wastewater solids which are regarded as organic products due to their organic content. Wastewater solids with high organic contents can be used as soil amendments in crop farms and lawns. It is important to note that the biosolids are only used in this manner after they have undergone treatment to remove and/or lower the levels of unwanted constituents (Burton et al., 2003).

2.1 Sludge from Wastewater Treatment Works

2.1.1 Sources of sludge in wastewater treatment

The number and types of sources of sludge in wastewater treatment depend on the type of plant in general and unit operations and processes making up the treatment train in particular (Burton et al., 2003). A typical municipal WWTW consists of four segments: preliminary treatment, primary treatment, secondary treatment, and advanced treatment (Shuval, 1997).

Preliminary treatment can be achieved through screening and grit removal. Screening involves the use of bar screens to remove solids present in the wastewater. Grit removal facilities are used to separate the grit particles from the organic sludge. The aim of preliminary treatment is to protect downstream equipment from potential damage and blockage (Burton et al., 2003).

Primary treatment can be achieved through the use of PSTs to remove large organic solids (Shuval, 1997). PSTs are generally circular in shape with the floor of the tank sloping towards the centre. The solids and floating material contained in the wastewater settles towards the bottom of the tank due to gravity where they are ultimately removed for further treatment prior to terminal disposal (Burton et al., 2003).

Secondary treatment is oftentimes achieved through the use of biological treatment processes. Burton et al. (2003) mentions that the main objective of the biological treatment of domestic wastewater are to (1) transform dissolved and particulate biodegradable constituents into acceptable end products, (2) to capture and incorporate suspended and nonsettleable colloidal solids into biological floc, and (3) to transform and/or remove nutrients such as nitrogen and phosphorus from the wastewater.

There are two ways in which biological treatment processes can be configured, suspended growth processes and attached growth processes (Shuval, 1997).

In suspended growth process, the microorganisms which are used for treatment are kept in suspension by appropriate mixing. The most common suspended growth process used is the activated sludge process (Burton et al., 2003). This process can be carried out under aerobic, anoxic, and anaerobic conditions. In this process, the microorganisms are responsible for the conversion of biodegradable, organic wastewater constituents into new cell mass and byproducts, which are subsequently removed downstream by means of settling (WEF, 2010).

In attached growth processes the microorganisms which are responsible for the conversion of organic material are attached to an inert packing material which could be rock, sand, or gravel. As the wastewater passes through the inert material, organic matter is removed (Burton et al., 2003).

Advanced treatment processes are used in order to meet disposal standards which may not be achieved through primary and secondary treatment. Advanced treatment processes may be combined with conventional treatment processes mentioned above or used as a separate treatment train after the biological treatment process (Shuval, 1997).

In all four segments of treatment discussed above, solid and semi-solid residues are removed which require treatment and disposal. In a typical municipal wastewater treatment plant coarse solids are removed during the screening process and heavy inorganic materials are removed by the grit removal facility. In the PST, the solids collected at the bottom of the tank often referred to as primary sludge also require treatment before they can be safely disposed off. In the activated sludge process, the microorganisms responsible for utilising the organic materials present in the wastewater become sludge. In the attached growth process, the microorganisms attached to the inert packing material when in contact with the wastewater generally settle to the bottom of the tank over a certain period of time, also contributing towards the accumulation of sludge (Shuval, 1997).

In summary, sludge is generated at various treatment processes, and at each of those stages, sludge is removed from the main wastewater stream for further treatment.

2.1.2 Characteristics of Sludge

The characteristics of solids which are removed during wastewater treatment processes vary from treatment works to treatment works, and, for a single treatment works from time to time. This variation is due to changes in the composition of the incoming wastewater as well as the type of treatment process(es) used.

The characteristics of these solids produced during the treatment of municipal wastewater depend on a number of factors including but not limited to the characteristics of the influent wastewater, use of chemical precipitants and coagulants in the treatment process, climate conditions, and selected treatment process (WEF, 2010).

The following highlights the characteristics and sources of solids from conventional activated sludge WWTW:

2.2 Sludge Treatment

Sludge generated during municipal wastewater treatment contains nutrients and organic carbon which may be used for beneficial purposes. Sludge generated from municipal WWTW in South Africa, after being processed, is generally used as a soil conditioner (Herselman & Moodley, 2009). Dependent on the envisaged beneficial use, the generated sludge has to go through a treatment process in order to meet the required standards for that particular beneficial use (McFarland, 2001). The treatment of sludge generated from municipal wastewater treatment is achieved by using a combination of the following processes:

- Preliminary operations
- Sludge thickening

- Stabilisation
- Conditioning
- Sludge dewatering

2.2.1 Preliminary operations

Preliminary operations in sludge processing are used to ensure that the sludge is relatively homogeneous prior to being conveyed to downstream processes. This is generally achieved by grinding, degritting, and blending (Karius, 2011). Grinding is used to cut large particles and long strings of materials into smaller particles so as to ensure that rotating machinery downstream is not prone to clogging or blockage (Burton et al., 2003).

Degritting is a process used to remove the grit particles from the sludge. This process is generally used when the WWTW does not have grit removal facilities or when the grit removal facilities are not designed to handle peak flows.

Since sludge that is processed is obtained from various sources and has varying characteristics, the sludge is collected and mixed together in order to result in a mixture which is uniform through a process called blending. Blending produces sludge that has uniform characteristics which gives rise to improvement in treatment plant efficiency (Burton et al., 2003).

2.2.2 Thickening

Sludge thickening is the process used in sludge treatment to reduce the water content of the sludge by removing some of the liquid present in the sludge, and thus resulting in an increase in solid content per unit volume (McFarland, 2001). The reduction in volume of sludge to be processed is important in that the size of downstream units will reduce, i.e., pumps, pipes, and tanks and in addition to this, the amount of chemicals required for the treatment process, and by extension the cost of downstream processing, will also diminish (Nilsson & Dahlstrom, 2005). The thickening of sludge from municipal wastewater is accomplished by using such physical unit operations as gravity thickeners, flotation thickening, centrifugal thickening, gravity belt thickening, and rotating-drum thickening (Burton et al., 2003).

Gravity Thickening

Gravity thickeners are similar in structure to sedimentation tanks and are essentially regarded as settling tanks with or without mechanical thickening devices (Kos, 2013). Gravity thickeners are generally circular in shape and the incoming waste stream is fed through the center of the structure. The incoming stream is brought through the center to minimise turbulence which may come about as a result of the feed entry velocity and also to ensure that the incoming slurry is below the clear-liquid surface (Andreoli et al., 2007). As with sedimentation tanks the heavy solids settle towards the bottom of the tank by means of gravity. The solids are then diverted towards the center of the tank through the use of scrapers, where they are ultimately removed for further treatment. The supernatant is collected at the top of the tank through the use of overflow launder and it is returned to the head of works (WEF, 2010).

The design basis of a conventional gravity thickener is based on the settling velocity of the particles by means of gravity exceeding the upward velocity of the clarified water flowing upwards towards the surface of the liquid (Andreoli et al., 2007).

Floatation Thickening

Floatation thickening refers to the process which causes sludge to rise towards the surface of the tank where it is skimmed off and collected. This process is achieved by the introduction of air, in the form of fine gas bubbles, into the DAF thickener. The solid particles present in the liquid attach to the air bubbles making them buoyant. The solid particles are then able to rise to the surface of the liquid where they are subsequently removed by a skimmer and discharged into a float collection box (WEF, 2010).

Floatation thickening is generally used in cases where activated sludge has not thickened to the required standard in gravity thickeners. This type of thickening is considered to be a suitable thickening method for both sludge from chemical treatment processes and sludge from biological treatment processes (Nilsson & Dahlstrom, 2005). Floatation thickening is also used in WWTW where the removal of biological phosphorus is required. In such applications the sludge is kept under aerobic conditions to prevent the release of phosphorus back into the liquid phase as dissolved phosphorus (Andreoli et al., 2007).

DAF tanks can be fitted with both surface skimmers and solids removal devices at the bottom of the tank. The solids removal mechanism fitted at the bottom of the tank is for heavier solid particles that settle on the floor of the tank, and the surface skimmers are for the removal of the suspended solids (WEF, 2010).

2.2.3 Stabilisation

Stabilisation of sludge is done to achieve the removal of bad odours, reduction of pathogen loads, reduction of vector attraction, and reduction or elimination of the potential for putrefaction (McFarland, 2001).

Stabilisation is also used to reduce the volume of the sludge by removing some of the liquid present as well as to produce gas which can be beneficial, e.g., methane. Stabilisation of sludge is generally achieved through alkaline stabilisation, anaerobic and aerobic digestion, and composting (Burton et al., 2003).

Alkaline stabilisation

Alkaline stabilisation is a process used to make the sludge unsuitable for most microbial communities. When lime is used to stabilise untreated sludge, it is added in quantities such that pH is increased to 12 or greater (Herselman & Dahlstrom, 2005). The increase in pH ensures that microbial metabolism is significantly retarded. The absence of a thriving microbial community results in sludge which neither releases bad odours nor putrefies (Burton et al., 2003).

Anaerobic digestion

Anaerobic digestion is a bacterial driven decomposition process which reduces the volume of sludge and stabilises the sludge. During this process, carbohydrates, fats, and proteins are converted into methane and carbon dioxide gases (Nilsson & Dahlstrom, 2005). The methane produced can be used to generate heat and/or electricity either of which can be used on site or transmitted for use elsewhere. Anaerobic digestion generally takes place in digestors where the temperature is usually kept at about 35 degrees Celsius, and the sludge is kept in the digester for approximately 20 days to ensure that the sludge is properly stabilised (Andreoli et al., 2007).

Aerobic digestion

Aerobic digestion is a process that takes place in a tank that is aerated (Nilsson & Dahlstrom, 2005). During this process microorganisms degrade the organic matter in the sludge into carbon dioxide, water and organic material. The harmful organisms present in the sludge are destroyed by subjecting the sludge to 50 to 60 degrees Celsius for approximately 5 to 6 days post-digestion (Karius, 2011).

The major drawback with using aerobic digestion as opposed to anaerobic digestion is the high energy cost associated with supplying the required oxygen and operating the tank at the required temperature (Burton et al., 2003).

Composting

Composting is a process, by which wastewater biosolids are stabilised. During this process, organic materials are decomposed into stable end products through biological degradation. The compost heats up to temperatures between 50 and 70 degrees Celsius which then results in the destruction of pathogenic organisms (Burton et al., 2003). Sludge which has been properly composted and is rich in nitrogen and phosphorus can be used as soil amendment (Andreoli et al., 2007).

Composting of sludge can be achieved under both aerobic and anaerobic conditions. However, most municipal WWTW compost sludge under aerobic conditions (Andreoli et al., 2007). Composting under aerobic conditions ensures the acceleration of material decomposition and it also results in a rise in temperature required for the destruction of pathogens (Burton et al., 2003). Composting is considered to be cost effective and it is popular amongst environmentally inclined people (Nozaic, 2013).

2.2.4 Conditioning

Sludge conditioning is a process that is aimed at improving the dewaterability of sludge by bringing about change to the solid's physical properties, and this process is generally carried out prior to dewatering. Sludge can be conditioned through the use of such chemicals as lime, alum, and organic compounds as well as through thermal treatment (Andreoli et al., 2007).

The addition of chemicals results in the coagulation of suspended solids which in turn releases some fraction of the absorbed water (Burton et al., 2003). The origin of sludge to be conditioned partly determines the amount of chemicals needed to condition the sludge. Sludge with characteristics that render it difficult to dewater always require larger amounts of chemical conditioners, and typically gives rise to a wetter cake and nutrient-rich effluent.. Depending on the method of ultimate sludge disposal high levels of nutrients in the sludge can cause problems in the receiving environment.(Burton et al., 2003).

The intended methods of thickening, dewatering and disposal of sludge post-treatment should all be taken into consideration when selecting the method of conditioning. For example, the performance of belt-filter press, rotary drum and gravity belt thickeners is improved if the incoming solids have a uniform floc size that increases the voids between particles, and pressure filtration and sand bed filtration dewatering methods perform well when the sludge has been chemically conditioned (WEF, 2010).

2.2.5 Dewatering

Dewatering is a process used to bring about a decrease in the amount of water contained in sludge. Sludge dewatering is carried out in order to achieve one or more of the following, 1.) Reduction of cost of transporting sludge to terminal disposal site, 2.) Making sludge easier to handle, 3.) Preparing the sludge for incineration, 4.) Preparing the sludge for composting with little or no need to use supplementary bulking agents, 5.) Reduction of leachate production at landfill site (Burton et al., 2003).

Sludge dewatering can be achieved through mechanical and natural processes (Andreoli et al., 2007). Natural dewatering processes, often achieved through the use of sludge drying beds and sludge lagoons, rely on natural evaporation and percolation. Mechanical dewatering processes, often achieved through the use of centrifuges, filter belts, and filter presses dewater sludge at a quicker rate (Burton et al., 2003). Regardless of the chosen method, dewatering generates two products: solid cake and a liquid stream which has been removed from the incoming stream. The liquid is usually sent back to the head of works for further treatment (Nilsson & Dahlstrom, 2005; WEF, 2010). Land availability, type of sludge to be dewatered and the expected characteristics of the dewatered product should all be considered when selecting the appropriate dewatering method (Burton et al., 2003).

2.3 Disposal

Once the sludge generated during the treatment of the wastewater has undergone treatment in order to meet the discharge limits as set by the Department of Water and Sanitation; it can be disposed of in a variety of ways (Herselman & Snyman, 2006).

2.3.1 Incineration

Thermal treatment processes currently being used when disposing of sludge include incineration, co-incineration, and pyrolysis or starved air combustion. Incineration results in the total or partial combustion of organic solids to oxidised end products. Pyrolysis or starved air combustion achieves partial oxidation and volatilisation of organic solids to produce end products with energy. Co-incineration of sludge with other materials in industrial processes such as industrial furnaces and cement kilns is another process (Snyman, 2006).

When disposing of sludge through the process of incineration it is important to note that there are a number of pollutants that are released into the atmosphere. These pollutants may be nitrogen oxides, carbon dioxide, organic compounds, fly ash, particulates, and heavy metal vapours (Nilsson & Dahlstrom, 2005). These gases need to be monitored so as to ensure that there is no risk to the receiving environment as well as to protect the public (Snyman, 2006). After the sludge has gone through the process, ashes remain that require disposal, usually at a designated disposal area or landfill site.

2.3.2 Agricultural use of sludge

Sludge that has undergone treatment process can be utilised as a soil amendment in agricultural lands. When sludge is used as a soil amendment the rate of application is very important. For instance, nutrients that are being applied over and above the required amount may make their way through the permeable soil into the groundwater, hence resulting in the contamination of groundwater (Snyman & Herselman, 2006). The sludge may also contain metals and micronutrients, and if the rate at which the sludge is being applied is high, this may lead to a build-up of metals in the soil which will in turn compromise the quality of soil (Snyman & Harselman, 2006). In some cases, it may be necessary to store some of the treated sludge prior to being applied on land so as to avoid applying the sludge at a high continuous rate. At the same time, the stored sludge should not be kept for a long period which may result in the regrowth of pathogens and other unwanted constituents (Nilsson & Dahlstrom, 2005).

The receiving environment is usually located away from the WWTWs which means that the sludge has to be transported to the final disposal site. The sludge may be transported to final disposal sites using pipelines, trucks and/or rail (this is not popular in South Africa). When dealing with liquid sludge a closed vessel is usually a popular method of transportation as this reduces the risk of spills, odours and the dissemination of pathogens (Burton et al., 2003).
Based on the South African Guidelines for the Utilisation and Disposal of Wastewater Sludge: Volume 4 (2006), when transporting sludge to the disposal site, it should be handled as a hazardous material due to it containing infectious agents. It is therefore important to focus on the following during the transportation process:

- The person tasked with the responsibility of transporting the sludge must be given enough information regarding the nature and properties of the load.
- The vehicle to be used for transportation of the sludge must be sealed and fitted with a Hazchem placard.

The disposal of sludge containing high amounts of pathogens can create environmental and health problems in the receiving environment. It is widely known that waterborne infections are most likely to be transmitted through the oral-faecal route. Infected individuals can shed large numbers of pathogens each time they defecate. Once excreted, the pathogens can be transmitted to other individuals, animals, and sometimes inanimate objects which creates potential for the spread of diseases. Waterborne bacterial pathogens are associated with a number of diseases including but not limited to cholera, typhoid, paratyphoid, and salmonellosis. Enteric viruses that may infect humans include but are not limited to adenoviruses, enteroviruses, hepatitis A virus, and reoviruses. Apart from bacteria and viruses, humans can also be infected by a number of protozoa and helminths i.e. parasitic worms. Species of protozoa known to be pathogenic to humans include but not limited to giardia lamblia, balantidium coli and entamoeba histolytica. Theses protozoa are often passed as cysts in faeces of infected individuals. Problematic helminths are those that can be spread, as eggs or larva, through excreta (Westcot, 1997).

At the Darvill WWTW, all four types pathogens are monitored to ensure compliance with the discharge limits by comprehensively testing both sludge and final effluent prior to discharging into the receiving environment. In addition to this, tests are conducted on the various monitoring boreholes located at the sludge land to monitor levels of nutrients such as phosphorus and nitrogen as well as *E.coli* to ensure compliance with the discharge limits and to protect the receiving environment.

2.3.3 Landfill/Deposition Disposal

Treated sludge is sometimes disposed off at a dedicated landfill sites. The treated sludge can be disposed of within the property boundaries of the WWTWs (on-site disposal) or outside the property boundaries of the WWTWs (off-site disposal) (Snyman & Herselman, 2006).

When disposing of sludge at a dedicated landfill site, there are two options that can be adopted (Meozzi, 1997):

- Mono-disposal: where the landfill site is dedicated for sludge disposal only.
- Co-disposal: where the landfill site is used for sludge disposal as well as municipal solid waste disposal.

There are a number of factors that one needs to consider when selecting a suitable site for disposing of sludge. The factors to be considered include but not limited to:

Topography

As a minimum, the proposed site should be checked for any risks for runoff and erosion, and in addition to this it should be investigated whether or not the site falls within the 1:100 year flood line of surface water in order to avert the risk of polluting surface water (Burton et al., 2003). It should be noted that a more detailed investigation is required prior to the final selection of a disposal site, and in addition to this, new disposal sites require the completion of an Environmental Impact Assessment (EIA).

Soil characteristics

The characteristics of the soil at the site under consideration must be such that it does not promote the leaching of contaminants into groundwater. The pH of the soil must also be considered so as to check whether or not the conditions can result in the leaching of metals through the soil profile. The current condition of the soil at the proposed disposal site are investigated (concentration of nutrients, trace elements and metals) and recorded so that they can be used to monitor the changes in concentrations as a result of applying sludge onto the disposal site (Snyman & Herselman, 2006).

Surface Water

When one considers using a site that is in close proximity to a water body, it is important to conduct a study that will check the likelihood of the surface water being contaminated due to the presence of the sludge disposal site. Samples are taken from the water body likely to be contaminated and the results obtained are used to monitor any fluctuations as a result of the presence of the disposal site (Garg, 2009). Samples that are taken from the water body vary spatially and are taken over a predetermined period of time in order to give a good representation of the water quality.

Groundwater

Disposal sites that are located in close proximity to areas with a fairly high water table need to be given special attention as pollutants from the sludge being applied on land may make their way through to the groundwater and effectively compromise the quality of the water

(Burton et al., 2003). The quality of the groundwater needs to be tested so that it can be used to give baseline information to monitor any changes as a result of the sludge application. Monitoring boreholes are placed in strategic areas to monitor the water quality (Snyman & Herselman, 2006).

Heavy metals are one of the most persistent class of pollutants associated with wastewater. Heavy metals commonly found in wastewater include As, Cd, Cr, Cu, Pb, Hg, Ni and Zn. The release of high amounts of any of the aforementioned heavy metals into water bodies can potentially create health and environmental problems. Negative impacts on plant growth and health include the decrease in rate of seed germination and lipid content (linked to the presence of Cd and Ni), decrease in plant growth and enzyme activity (linked to the presence of Cr), the hindrance of photosynthesis (linked to the presence of Cu and Hg). Negative impacts on animal health include rise in blood pressure, kidney and brain damage, decline in fertility of men through sperm damage, diminishing learning ability of kids (linked to the presence of Pb), respiratory challenges such as asthma, chronic bronchitis (linked to the prsence of Cr and Ni), lung, nasal and sinus cancer (linked to the presence of Cr, Ni and Cd), liver damage and in some cases death (linked to the presence of Cu) (Achmad et al., 2017; Akpor et al., 2014; Tiwari et al., 2013).

Nutrients that wash into water bodies are often due to human activities, i.e. agriculture, stormwater runoff and wastewater treatment plants. The application of animal manure, application of fertilizers to crops and fields, as well as soil erosion can all contribute towards the release of nitrogen and phosphorus from agricultural lands. Stormwater runoff, which contains pollutants from sidewalks and roads, can also have high levels of nutrients. Wastewater treatment plants are also a source of nutrients due to the inefficient removal of nitrogen and phosphorus (EPA, 2017).

The discharge of excessive amounts of nutrients into water bodies can have negative impacts on human health and environment health. One of the environmental effects of excessive levels of nutrients in water bodies is eutrophication. It is worth noting that algae form a natural part of the ecosystem and that most algae species are not harmful to the environment. However, excessive amounts of nutrients can trigger algal blooms which can result in the depletion of oxygen in the water body, attenuation of sunlight penetration into the water body, as well as the production of toxins (Stubbs, 2016).

In addition to the negative environmental impacts listed above, the presence of excessive amounts of nutrients in water bodies may cause health problems to humans and animals as a result of ingestion of contaminated water. Health problems associated with the ingestion of water contaminated with heavy metals include methemoglobinemia, which is a blood disorder resulting in an abnormal amount of the methemoglobin that interferes with the body’s ability to release oxygen to body tissue. In addition to this, other health problems caused by consuming water contaminated with excess nutrients include cancer, adverse reproductive disorders, diabetes and thyroid conditions (Stubbs, 2016).

Buffer zones

Buffer zones are needed to separate sludge disposal sites from sensitive areas including but not limited to residential areas, surface waters or boreholes, groundwater and property boundaries (Snyman & Herselman, 2006). Buffer zones are generally located alongside a water body and essentially function (Jorgensen, 2009):

- To filter polluted overland and subsurface flow from the sludge disposal site.
- To protect the banks of water bodies against erosion.
- To filter polluted air from the sludge disposal site.

Typical sites with significant overland flow to the buffer, low berms can be used to intercept concentrated flow and spread it before it enters a forest buffer. The forest buffer can assist with the removal of sediments prior to flow entering the water body. Buffers may accumulate significant amount of sediment and nutrients over time. It is therefore important that the vegetated buffers be mowed and the settled solids be removed from time to time to ensure that it continues to operate efficiently.

2.4 Summary

A typical municipal WWTW consists of four segments preliminary treatment, primary treatment, secondary treatment, and advanced treatment. Solids and biosolids get produced from all four segments. Theses solids and biosolids require treatment prior to disposal in order to protect public health and the environment (ICE, 1985). The treatment of sludge generated from municipal wastewater is achieved by using a combination of a number of processes including preliminary treatment, dewatering, thickening, stabilisation, and conditioning. Once the sludge generated during the wastewater treatment process has undergone treatment to meet discharge standards, it can be disposed of through incineration, agricultural application, and landfilling. The exact nature of treatment process of sludge removed from the wastewater treatment process is dependent on the envisaged beneficial use.

3. METHODOLOGY

3.1 Introduction

Darvill WWTW is currently undergoing an upgrade, to increase its treatment capacity from 65Ml/d to 120Ml/d, in order to accommodate current and future flows (Westgate, 2014). With the increase in treatment capacity, the volume of sludge, from wastewater treatment, will also increase, which leads to the need to assess the current sludge disposal method against the new treatment capacity. As stated in Chapter 1, the objectives of this study were to:

- Assess the sludge disposal method currently employed at Darvill WWTW against current design flow.
- Assess the sludge disposal method currently employed at Darvill against future design flow, to establish whether the current sludge disposal method will be sufficient for the new treatment capacity, in terms of discharge standards set for sludge disposal by land application.
- Assess the fate of heavy metals and nutrients at the Darvill WWTW including the sludge land.
- Make a recommendation on the amount of sludge that may be disposed of by land application.

To achieve the above listed objectives detailed field and laboratory studies were carried out. Where necessary, historical data from Umgeni Water's database was analysed to provide insight into some issues of interest to the study.

Historical data was relied upon to estimate heavy metal concentration in wastewater and soil. The heavy metal concentration for each soil sample was compared to the maximum permissible level (MPL) of heavy metals for soils receiving high sludge loading rates to check compliance with the guidelines for utilisation and disposal of wastewater sludge (volume 4) (Herselman & Snyman, 2006). The heavy metal concentration for each soil sample and the heavy metal concentration in the sludge that will be applied to the Darvill sludge land are used to determine the permissible application rate (PAR).

Laboratory/Field studies were used to determine the soil moisture content and soil bulk density of soil samples taken from the Darvill sludge land as described in section 3.6 below. The soil moisture content and soil bulk density are required in order to be able to determine the amount of solute retained in soils. These parameters were used in the model created to predict the future concentrations of heavy metals present in soils, the significance of the afore mentioned will be discussed in more detail later in the report.

Prior to sampling of soil at the Darvill sludge land the number of samples to be taken and the location of the samples to be taken was determined as detailed in section 3.3 below. When choosing sampling sites there are several factors that were taken into consideration, i.e., the sampling points were varied spatially in order to give a good representation of the sludge land, the topography of the sludge land, and the proximity of the Msunduzi River. The majority of the site slopes gently in a north easterly direction towards the Msunduzi River see figure 3.1 and 3.2 below. Due to the topography of the site, monitoring boreholes have been placed in strategic areas to monitor the water quality in order to monitor compliance with the guidelines and standards set by the Department of Water and Sanitation (Herselman & Snyman, 2006).

The next step was to arrange consent, to conduct tests on the Darvill sludge land, with the property owner, i.e. Duzi Turf. Once this was organised, pegs were placed to mark proposed test pits. Following this the land owner assessed whether or not any buried services may be affected by sampling and then the selection of sampling sites was finalised. Following the selection of sampling sites, six test pits (dimensions of 1m x 1m x 0.6m) were dug for sample collection. The purpose of sampling of soil was to obtain the soil characteristics in order to determine the amount of solute retained, see section 4.2 "Results" below on page 65 for a detailed explanation on how soil characteristics are used to determine amount of solute retained. The sampling depth chosen for the purpose of this research report is because the available soil data, namely the concentration of heavy metals present in the soil, obtained from the plant is up to a depth of 0.6m. The reason for doing test pits was not to locate the depth of groundwater. The depth of groundwater can be determined by drilling until you reach groundwater (which is outside the scope of research). It should be noted that the soil profile was not determined for this research report.

3.2 Model rationale

The model presented in this study is used to predict future concentrations of heavy metals that can be expected in the soil when biosolids are applied as a soil amendment. The information obtained from the model can be used by plant operators to apply mitigation measures which are intended to reduce the concentration of heavy metals present in the soil, i.e., reduction of heavy metal concentration at the source (industrial waste) by means of pre-treatment in order to adhere to the disposal limits as set by the Municipality, maintenance of sewer pipes and manholes to reduce stormwater infiltration, sludge land rehabilitation by means of removal of top soil and application of lime in order to increase pH of acidic soil.

3.3 Study area

The study focuses on the Darvill WWTW which is responsible for treating the majority (approximately 99.6%) of the wastewater generated by the area which falls under the Msunduzi municipality in Pietermaritzburg, with the remainder of the wastewater being treated at the Howick WWTW. The Darvill WWTW is located on the western outskirts of Pietermaritzburg, in an area situated on the banks of the Msunduzi River. For the most part, the site slopes gently in a north easterly direction at about 1m in 27.5m as can be seen on figure 3.1 below.

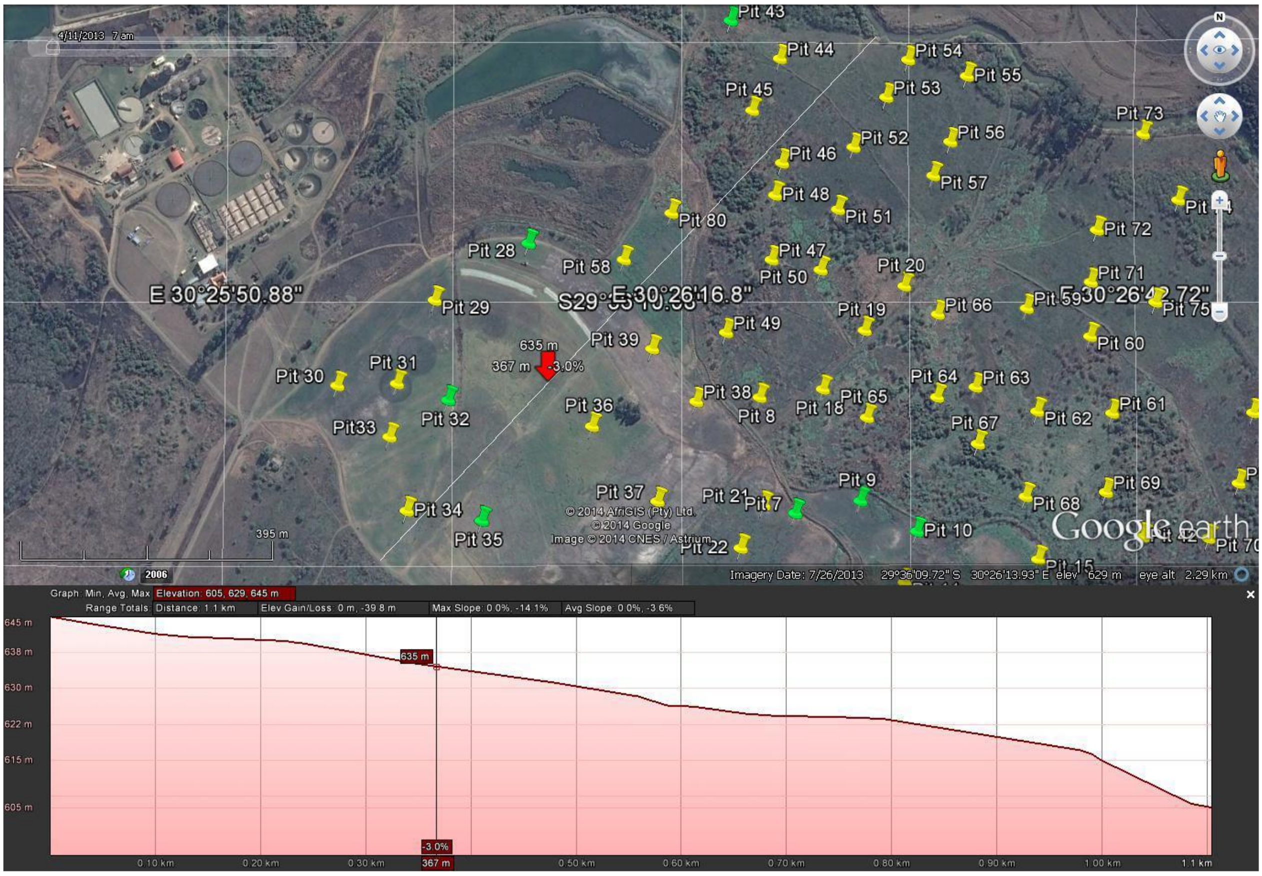


Figure 3.1: Satellite image and cross section of Darvill sludge land (Bester & Hughes, 2014).

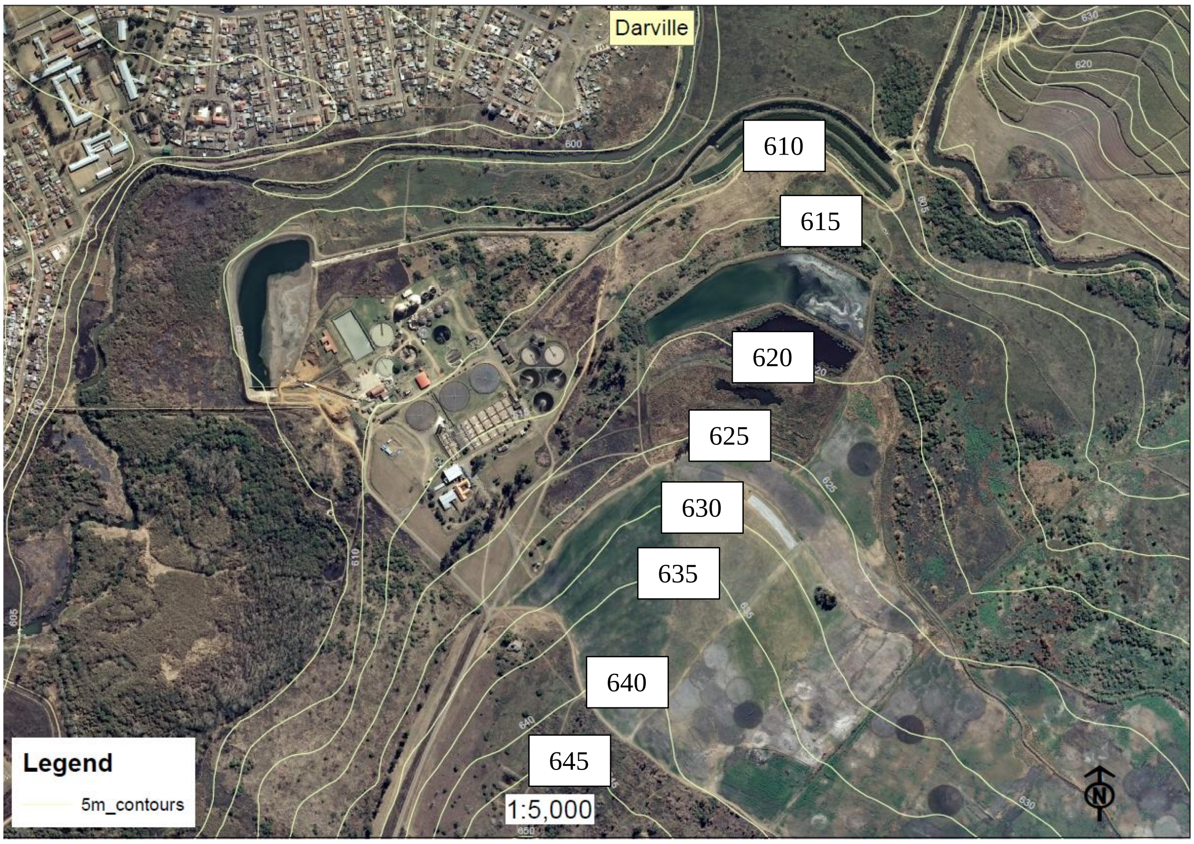


Figure 3.2: Darvill sludge land with 5m contours

3.4 Selection of sampling sites

The soil samples were all collected from the Darvill sludge land which is located in the southeast direction of the WWTW, see figure 3.1 above. Four out of the five sites from which soil samples were obtained were located downstream of the Darvill sludge land which is located closest to the Msunduzi River. When choosing sampling sites there are several factors that were taken into consideration, i.e., the sampling points were varied spatially in order to give a good representation of the sludge land, the topography of the sludge land, and the proximity of the Msunduzi River. For the purpose of this research, soil sample 4 was used for detailed evaluation. There are two main reasons why this site is the only site chosen for in depth evaluation. First, the site is easily accessible. Second, the site is the closest to the Msunduzi River, and lies downstream of all the four sites. Thus sampling at this site provides a more probable estimation of the heavy metal loading into the river.

3.5 Tests carried out

One sample of effluent collected from the Darvill WWTW, daily, was screened for heavy metals. The concentration of Cd, Cr, Cu, Pb, Hg, Ni and Zn were determined by measuring the emission signal using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). The concentration of As present in the wastewater sampled from the Darvill WWTW was determined by using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) system.

The ICP-OES is an analytical technique that is used to detect heavy metals in water and wastewater samples. This uses a plasma source to excite the atoms which are present in water, resulting in the excited atoms emitting light of a characteristic wavelength. The intensity of the light that is emitted by the excited atoms is measured, and the measured intensity can be related to the concentration of the heavy metals present in the wastewater (Baysal et al., 2013).

The ICP-MS technique is a multi-element technique which uses a plasma source to atomize a sample, by doing so it allows or the detection of the ions by using a mass spectrometer. The mass spectrometer allows for the separation of ions in accordance to their mass to charge ratio.

Samples that are analysed by using the ICP-MS technique can be introduced in 3 different forms, i.e. aerosol, liquid or solid phase (Bazilio & Weinrich, 2012).

3.6 Collection of soil samples

The apparatus used to collect soil samples include a Tractor-Loader-Backhoe (TLB), shovel, hammer, steel ring, and sealable plastic bags.

As mentioned above, the TLB (see figure 3.3) was used to dig test pits (1m x 1m x 0.6m) to expose the soil layer to be sampled. Samples were taken immediately after digging the test pits so as to ensure that the recorded soil moisture content is a true reflection of the conditions on the ground. The steel ring (core) was then placed at the bottom of the excavated test pit and hammered gently using a hammer (see figure 3.4). A shovel (see figure 3.5) was then used to carefully dig around the steel ring without disturbing the soil contained in the ring, and the ring was subsequently removed. Prior to placing of soil samples into labelled plastic bags, excess soil from the steel ring was removed by using a spatula. Samples were then placed in plastic bags which were labelled with the sample collection point, date of sample collection and the depth at which the sample was collected, and transported to the Umgeni Water laboratory for testing.

Figure 3.3: Tractor-Loader-Backhoe.

Figure 3.4: Steel ring (core) (Brown & Wherrett, 2018)

Figure 3.5: Shovel

3.7 Laboratory procedure

The laboratory procedure that was used for analysing the soil moisture content and bulk density was as per Umgeni Water's standard soil testing manual (Umgeni Water Laboratory Services, 2009). All analysis was completed within 48 hours of sample collection.

3.6.1 Soil moisture content and soil bulk density

Labelled oven proof dishes were placed on balance and the reading on the balance was returned to zero by pressing "tare" (see figure 3.6). Soil samples were removed from the sealable plastic bags and placed on labelled oven proof dishes and the weight of the wet sample was recorded (see figure 3.7 and 3.8). It should be noted that the entire volume of core was used for the below mentioned procedure in order to determine the soil moisture content as per equation 3.2 below. The labelled soil sample was then placed in the drying oven (see figure 3.9 and 3.10) and left overnight to dry at a temperature of 105^{o}C. The soil sample was then removed from the oven and placed on the balance. The dry weight was recorded for each sample and the results were recorded. The oven-drying method is the standard laboratory method used to determine the moisture content of a soil. For many soils, the mass of the dry solid particles is equal to the equilibrium dry mass, corresponding to an oven drying temperature of slightly above 100^{o}C, which ensures the complete evaporation of the pore water into the atmosphere within the drying over. This method assumes that the reduction in the sample mass is entirely due to the evaporation of the pore water, therefore the mass of pore water is taken to be equal to the reduction in mass of the wet soil sample (O'Kelly, 2004).

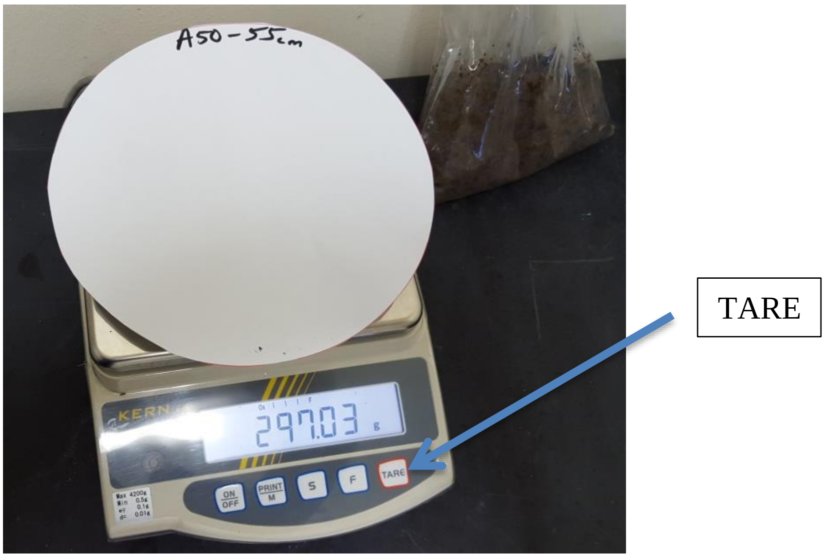


Figure 3.6: Balance

Figure 3.7: Balance set to 0.00g.

Figure 3.8: Weight of moist sample.

Figure 3.9: Oven set at 105 °C.

Figure 3.10: Soil samples placed in oven.

The above mentioned procedure was conducted in order to be able to determine the soil moisture content and the soil bulk density. The moisture content and the bulk density are required in order to be able to determine the amount of solute retained in soils. Using the dry mass and wet mass of soil samples taken, the soil moisture content and bulk density were calculated as follows:

$$Moisture\ content\ (\theta) = \frac{Moist\ weight\ (W_{wet}) - Dry\ weight\ (W_{dry})}{Dry\ weight\ (W_{dry})}\ x\ 100\% \qquad (3.1)$$

$$Bulk\ density\ (\rho_b) = \frac{Dry\ weight\ (W_{dry})}{Core\ volume\ (V_{core})} \qquad (3.2)$$

Hot plate nitric acid digestion

The first step in the digestion process was to accurately measure 250ml of soil water sample and to place it into a beaker and thereafter adding 12.5ml of concentrated nitric acid. The beaker was then covered using a watch glass, heated to bring solution to boil under a fume cupboard, and allowed to evaporate to about 50ml on a hot plate. The sample was then removed from the hot plate and allowed to cool to room temperature. Where necessary, the samples were filtered with 0.45µm membrane filter and Whatman 2V paper to remove colloidal particles. The sample was then quantitatively transferred into a volumetric flask (250ml) which had been rinsed with nitric acid, made up to the mark using ultrapure water. The made up sample was then transferred into a storage polyethylene bottle for all analyses that were required. The required aliquot (1 – 2ml) was then transferred and analysed by using the ICP-OES.

Hot plate aqua regia digestion

The process involved weighing approximately 4g of sample using a balance and then transferring the weighed sample into a glass beaker. The next step involved the addition of 60ml of ultrapure water and 40ml aqua regia (3:1 v/v HCL: HNO_3) and then covering with watch glass. The sample was then placed on a hot plate and left on the hot plate until near dryness. Once the sample was near dryness, it was removed from the hot plate and allowed to cool. 40ml of 2% HNO_3 was then added and transferred into a 500ml volumetric flask. Prior to the HNO_3 being transferred into the volumetric flask, it was filtered by passing it through filter paper (Whatman 2V). The sample was then made up to the mark (500ml) by using ultrapure water and then transferred into a polyethylene bottle for all analyses which were required. The required aliquot (1 – 2ml) was then transferred and analysed by using the ICP-OES (see figure 3.10).

Figure 3.11: Inductively coupled plasma optical emission spectrometer (ICP-OES).

Wastewater samples to be analysed by means of ICP-MS (see figure 3.12) had to first go through a pre-treatment stage which involved the digestion of the wastewater sample by means of adding acid. 400ml of the wastewater sample was transferred into a beaker which contained 4ml of concentrated nitric acid. The digested sample was then placed on a hot plate where it was heated so as to allow the sample to evaporate to about 100ml or before precipitation took place. Once the evaporation process had taken place, the sample was then removed from the hot plate and allowed to cool at room temperature. The next step in the pre-treatment process was to make up the sample to 400ml by adding ultrapure water using a volumetric cylinder. Prior to analysing the wastewater sample, the required amount of sample to be analysed was filtered through a 0.45µm filter. The required aliquot was then poured into the sample vial and analysed on the ICP-MS. The instrument was used according to the manufacturer’s instructions.

Figure 3.12: Inductively coupled plasma mass spectrometer (ICP-MS).

4. RESULTS AND DISCUSSIONS

In this chapter the results obtained from this research are presented and discussed. The chapter ends with an estimation of the number of years left before the MPL for each heavy metal, currently present in treated sludge, can be reached at the Darvill sludge land as well as a presentation of alternative measures that can be adopted to prolong the lifespan of the Darvill sludge land.

4.1 Background

Soil samples were collected from five different locations at the Darvill sludge land. Each location was sampled at five depths: 100mm, 200mm, 300mm, 400mm and 500mm. These samples were analysed for As, Cd, Cr, Cu, Pb, Hg, Ni and Zn. Concentrations of heavy metals in effluent wastewater and soil impacted by sludge disposal were obtained from Umgeni Water's database. All historical data used in this research report is from 2013. Guidelines for the Utilisation and Disposal of Wastewater Sludge (Volume 4) (2006) were used to obtain the MPL of heavy metals for soil receiving high sludge loading rates.

As detailed in Chapter 1, the solids removed from the PSTs are pumped to the pre-thickener where further separation of the liquid and solid component takes place. The solids that settle to the bottom of the tank are then pumped into an anaerobic digester where stabilisation of the solids takes place. The activated sludge from the reactor basin is taken into the DAF tank where removal of suspended solids takes place. The solids from both the DAF tank and the anaerobic digesters are taken to the post thickeners; from the post thickeners the sludge is pumped to the Darvill sludge land for final disposal.

4.2 Results

The concentration of heavy metals present in the sludge from post thickener 1 and post thickener 2 are presented in figures 4.1 to 4.8 below in a form of a line graph. Each plot included measured concentrations of heavy metals present in post thickener 1 and post thickener 2. The y-axis depicts the measured heavy metal concentration and the x-axis depicts the time line in months.

Based on the available data from the Darvill WWTW, the post thickeners were sampled once a month and the data on the figures below is the concentration of heavy metals for each month as well as the average concentration of heavy metals for 2013. The sampling frequency for the post thickeners can be improved by conducting more regular sampling due to the large fluctuations that are experienced in a wastewater treatment works. The table below (table 4.1) shows the average monthly rainfall recorded at the Darvill WWTW. It should be noted that the significance of the results presented in figures 4.1 to 4.8 will be discussed in more detail later in the report.

Table 4.1: Rainfall Data for Darvill WWTW

Rainfall Data												
Sample date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	101	89	89	85	82	71	69	70	69	85	89	97

As can be seen in table 4.1, the average monthly rainfall were higher in summer than winter. Average monthly rainfall data was measured because based on the available data the sampling frequency for heavy metals were done once a month.

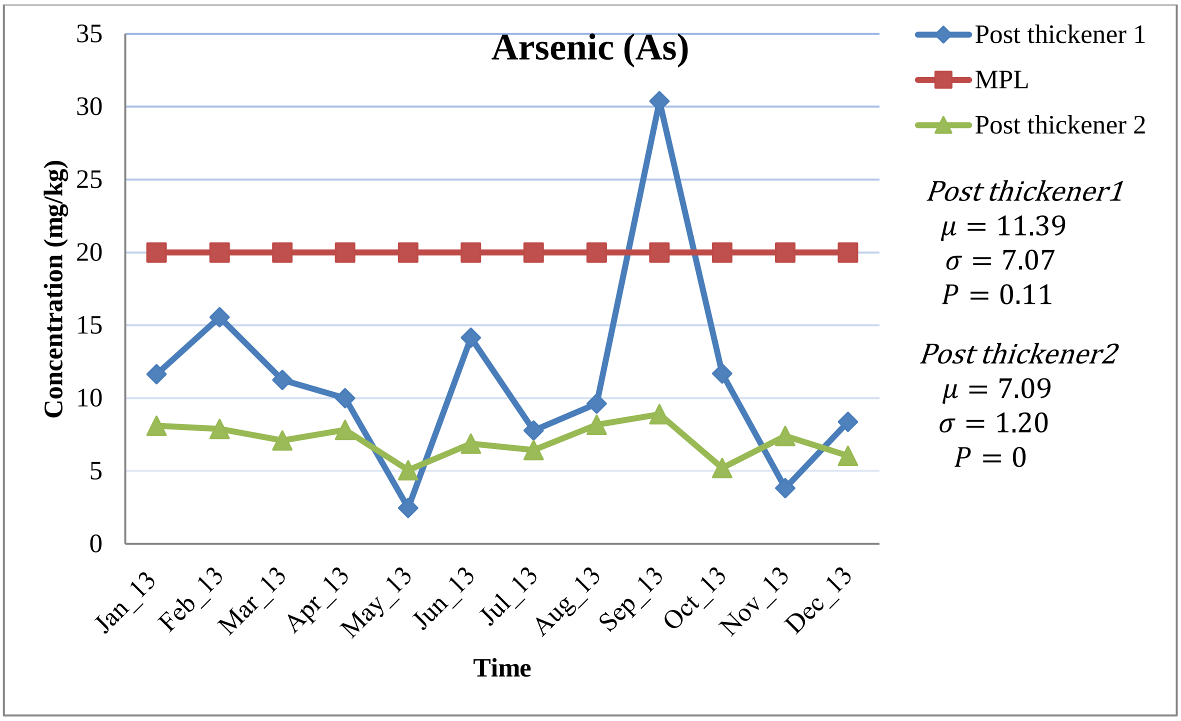


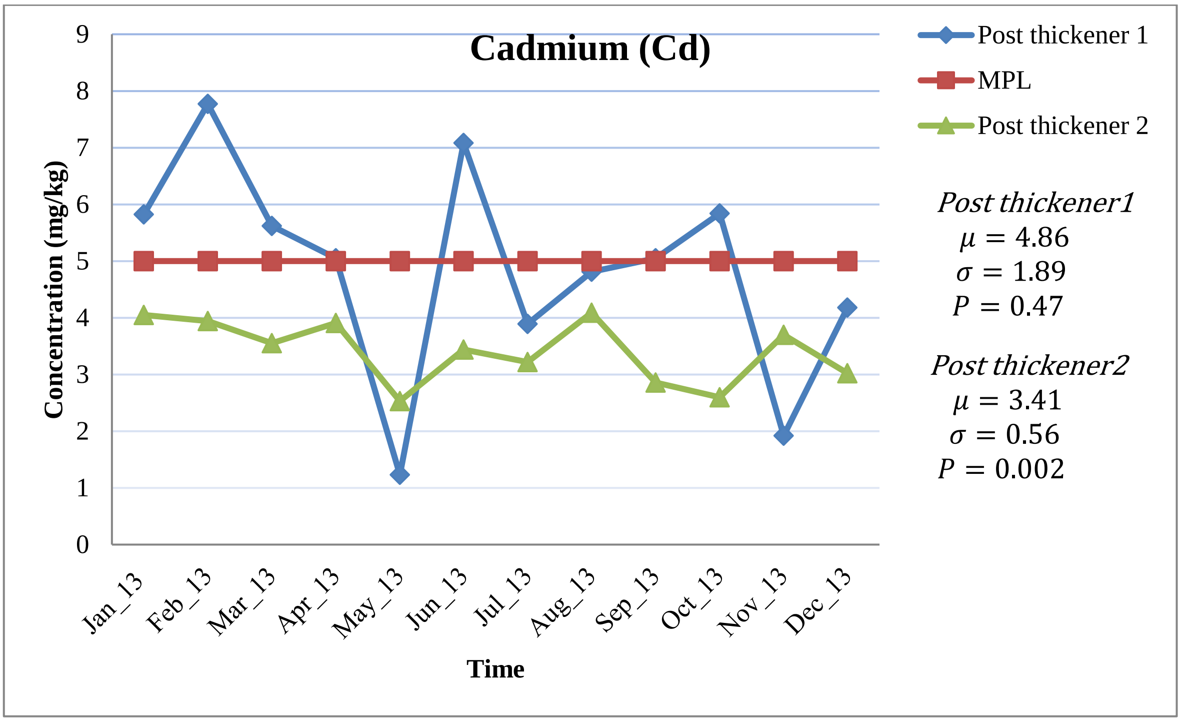
Figure 4.1: Concentration of As measured at post thickener 1 and post thickener 2.

At the Darvill WWTW, the solids removed from the primary settling tank (PST) are pumped to the pre-thickener, where further separation of the liquid and solid components take place. The solids are then pumped into an anaerobic digester where they are stabilized. The digested sludge from the anaerobic digesters is taken to post thickener 1. The activated sludge from the reactor basin is taken into the dissolved air flotation (DAF) tank where the removal of the remaining suspended solids takes place. The thickened waste activated sludge from the DAF tank is taken to post thickener 2. Refer to figure 1.1 above in Chapter 1 for a detailed process flow diagram.

The concentration of As was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.1. The concentration of As measured at post thickener 1 and post thickener 2 stayed below the MPL as required by the Guidelines for Utilisation and Disposal of Wastewater Sludge (Volume 4) (2006). It is noted that the measured concentration of As at post thickener 2 exceeded the MPL during the month of September. The maximum measured concentration of As was 30.4mg/kg, the minimum measured concentration was 2.5mg/kg, and an average concentration of 11.4mg/kg and 7.1mg/kg, for post thickener 1 and post thickener 2 respectively. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.1 above was determined and presented in figure 4.1. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0 and 0.11, respectively.

As can be seen on figure 4.1 above, the concentration of As present in post thickener 1 and post thickener 2 vary with time. This is due to the fact that the sludge present in both post thickeners comes from different points along the treatment train. It is also due to variations in constituents loading in the raw water. The quality of the industrial effluent that is directly discharged into the wastewater collection systems will have a direct impact on heavy metal concentration present in the wastewater.

It is also evident that the concentration of As present in post thickener 1 is higher than that of post thickener 2. This is expected as a large portion of the heavy metals present in wastewater is removed from the sedimentation tanks as part of the solids.



Post thickener1
$\mu = 4.86$
$\sigma = 1.89$
$P = 0.47$

Post thickener2
$\mu = 3.41$
$\sigma = 0.56$
$P = 0.002$

Figure 4.2: Concentration of Cd measured at post thickener 1 and post thickener 2.

The concentration of Cd was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.2. The concentration of Cd measured at post thickener 2 stayed below the MPL and as can be seen in the graph above, the concentration of Cd measured at post thickener 1 exceeded the MPL on five occasions. The maximum measured concentration of

Cd was 7.8mg/kg, the minimum measured concentration was 1.2mg/kg, and an average concentration of 4.9mg/kg and 3.4mg/kg for post thickener 1 and post thickener 2 respectively. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.2 above was determined and presented in figure 4.2. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0.47 and 0.002, respectively.

The concentration of Cd present in both thickeners vary with time, and this is due to the variations in constituents loading in the raw water, as well as the impact of the quality of industrial effluent that is directly discharged into the wastewater collection systems. As mentioned above, the probability of that the MPL of Cd will be exceeded is 0.47 which is of concern as the release of high amounts of Cd into the receiving environment can trigger health and environmental problems. The negative impacts associated with the release of Cd on plants include the decrease in the rate of seed germination and lipid content.

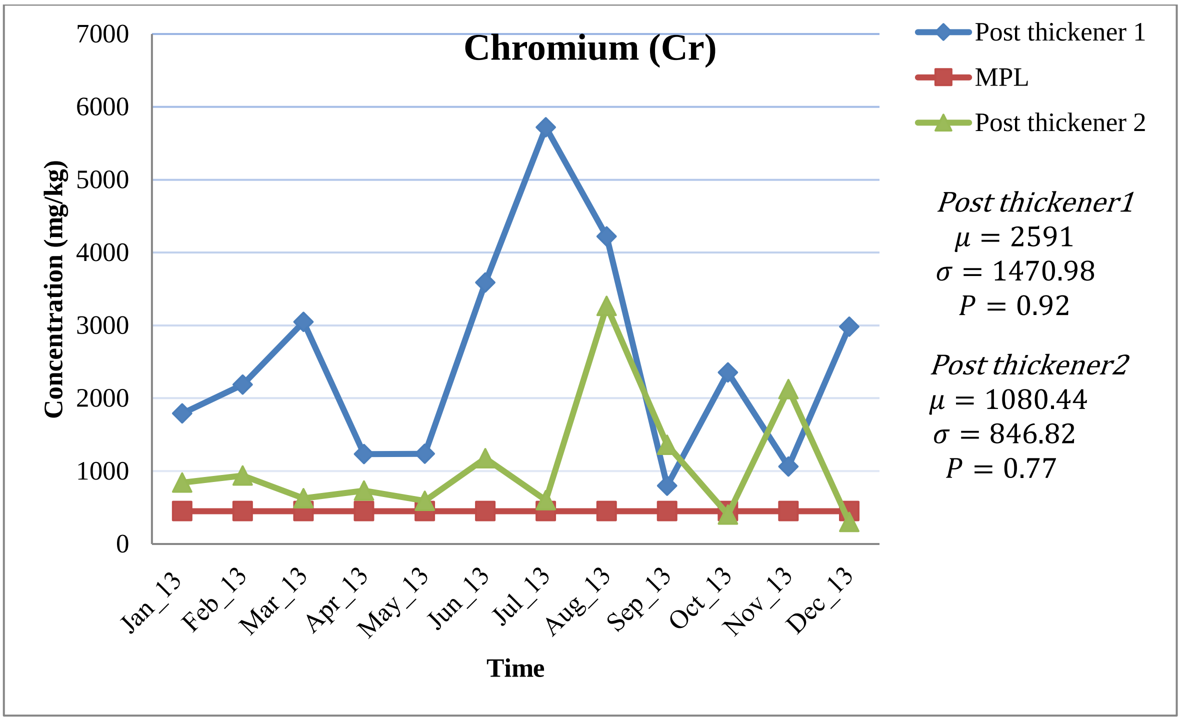


Figure 4.3: Concentration of Cr measured at post thickener 1 and post thickener 2.

The concentration of Cr was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.3. As can be seen from the graph, the measured concentration of Cr at post thickener 1 and post thickener 2 exceed the MPL. The graph above depicts an increase in the concentration of Cr in June, July and August 2013. The maximum measured concentration of Cr was 4 220.9mg/kg, the minimum measured concentration was 301.3mg/kg, and an average concentration of 2 519.0mg/kg and 1 080.4mg/kg for post thickener 1 and post thickener 2 respectively. The average concentration of Cr measured at both post thickener 1 and post thickener 2 exceed the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater Sludge (Volume 4). The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.3 above was determined and presented in figure 4.3. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0.92 and 0.77, respectively.

As can be seen in figure 4.3 above, the concentration of Cr present in post thickener 1 and post thickener 2 vary with time. The variation in concentration over time is due to the variations in constituents loading in the raw wastewater and the impact of the industrial effluent that is directly discharged into wastewater collection systems. It is also noted that the probability that the MPL will be exceeded is 0.92 and 0.77, for post thickener 1 and post thickener 2 respectively. This is of great concern as the negative impacts associated with the release of high amounts of Cr include reduced plant growth and enzyme activity.

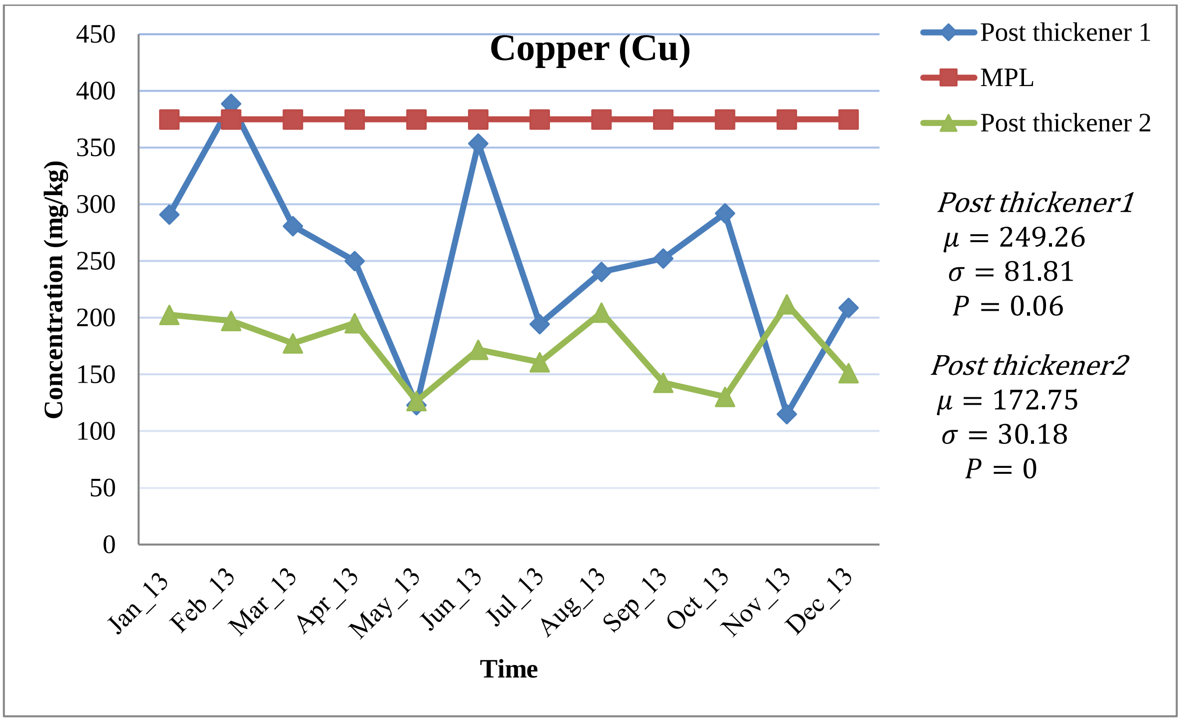


Figure 4.4: Concentration of Cu measured at post thickener 1 and post thickener 2.

The concentration of Cu was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.4. The concentration of Cu measured at post thickener 1 and post thickener 2 stayed below the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater Sludge (Volume 4) (2006). As depicted on the graph above, the concentration of Cu measured at pot thickener 1 and post thickener 2 stayed below the MPL, with the exception of one measurement recorded at post thickener 1 in February 2013. The maximum measured concentration of Cu was 388.7mg/kg, the minimum measured concentration was 115.0mg/kg, and an average concentration of 249.3mg/kg and 172.8mg/kg for post thickener 1 and post thickener 2 respectively. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.4 above was determined and presented in figure 4.4. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0.06 and 0, respectively.

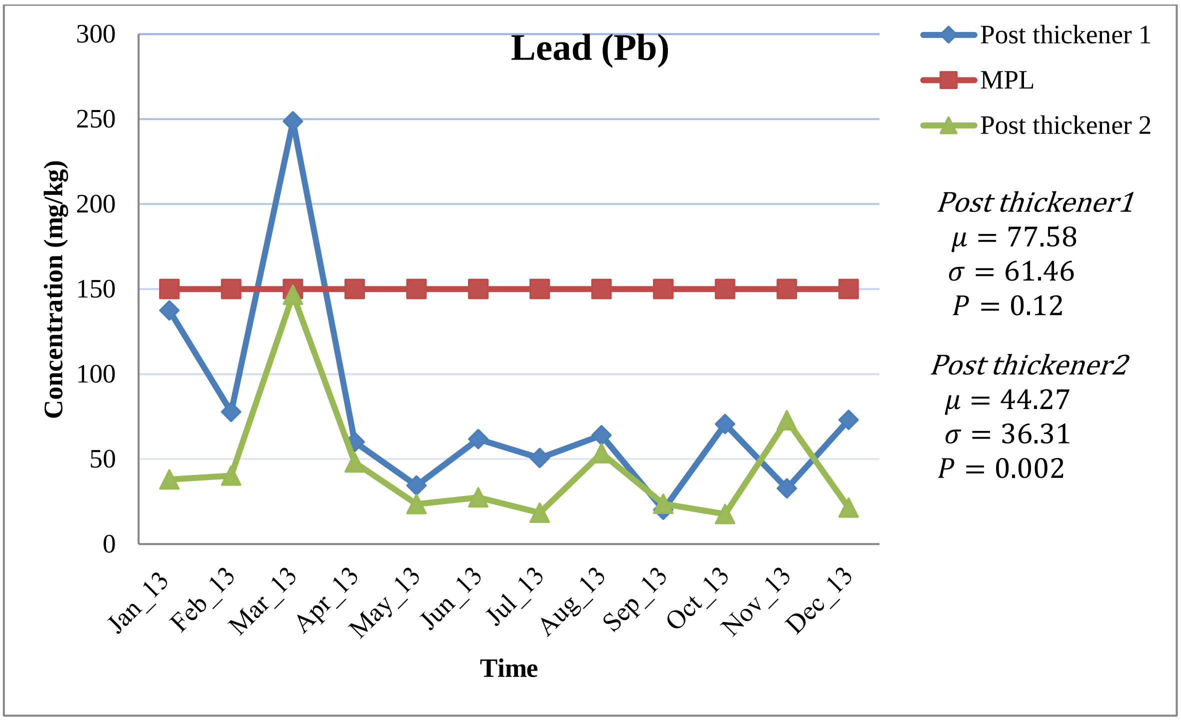


Figure 4.5: Concentration of Pb measured at post thickener 1 and post thickener 2.

The concentration of Pb was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.5. As can be seen from graph, the concentration of Pb measured at post thickener 1 and post thickener 2 stayed below the MPL, with the exception of one reading measured at post thickener 1 in March 2013. The maximum measured concentration of Pb was 248.6mg/kg, the minimum measured concentration was 17.7mg/kg, and an average concentration of 77.6mg/kg and 44.3mg/kg for post thickener 1 and post thickener 2 respectively. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.5 above was determined and presented in figure 4.5. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0.12 and 0.002, respectively.

As can be seen in figure 4.5 above, the concentration of Pb vary with time, due to variations in constituents loading in the raw wastewater. The quality of the industrial effluent that is directly discharged into the wastewater collection systems will have a direct impact on heavy metal concentration present in the wastewater.

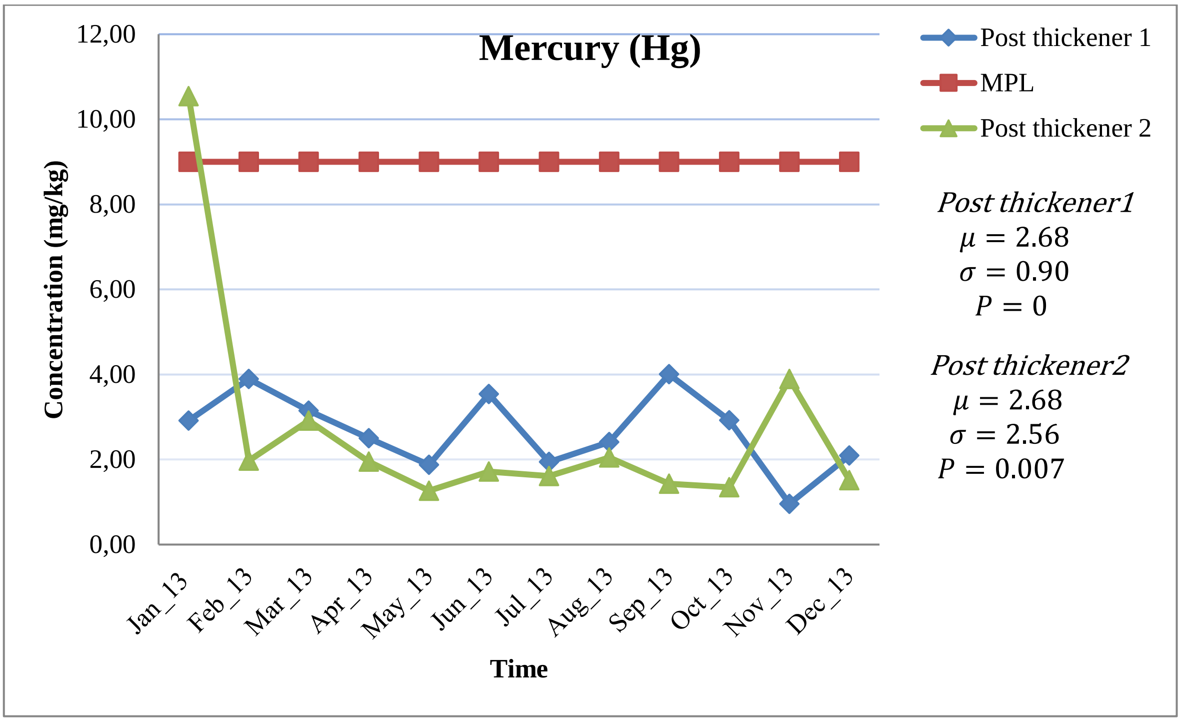


Figure 4.6: Concentration of Hg measured at post thickener 1 and post thickener 2.

The concentration of Hg was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.6. The concentration of Hg measured monthly at post thickener 1 and post thickener 2 stayed below the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater Sludge (Volume 4) (2006). As can be seen from the graph, the concentration of Hg measured at post thickener 2 in January 2013 exceeded the MPL. The maximum measured concentration of Hg was 10.5mg/kg, the minimum measured concentration was 0.96mg/kg, and an average concentration of 2.7mg/kg for both post thickener 1 and post thickener 2. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.6 above was determined and presented in figure 4.6. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0 and 0.007, respectively.

As can be seen in figure 4.6 above, the concentration of Hg present in both post thickeners vary with time due to the variations in constituents loading in the raw wastewater as well as the direct impact on heavy metal concentration as a result of the quality of the industrial effluent that is directly discharged into the wastewater collection systems. It is also noted that the concentration of Hg present in the post thickener 2 exceeded the MPL only once in a period of 12 months, therefore the likelihood of reoccurrence is low.

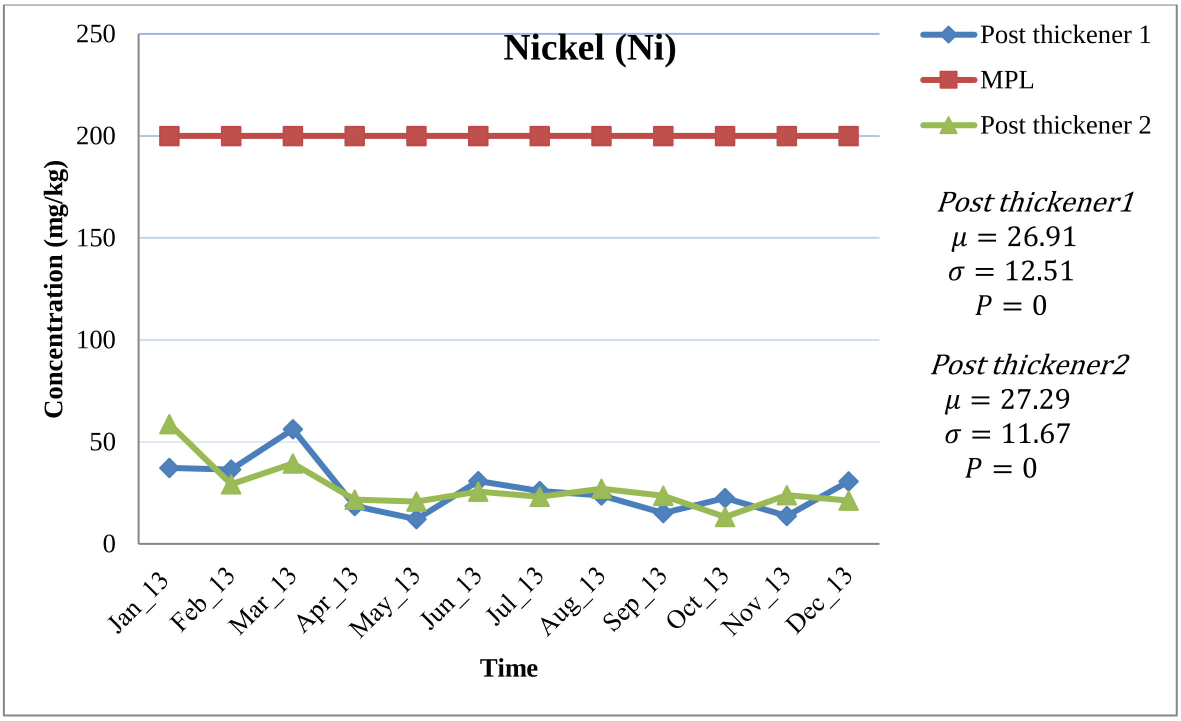


Figure 4.7: Concentration of Ni measured at post thickener 1 and post thickener 2.

The concentration of Ni was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.7. As can be seen from the graph above, the concentration of Ni measured monthly at post thickener 1 and post thickener 2 stayed below the MPL. The maximum measured concentration of Ni was 58.8mg/kg, the minimum measured concentration was 13.2mg/kg, and an average concentration of 26.9mg/kg and 27.3mg/kg for post thickener 1 and post thickener 2 respectively. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.7 above was determined and presented in figure 4.7. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0 and 0, respectively.

As can be seen in figure 4.7 above, the concentration of Ni present in post thickener 1 and post thickener 2 consistently remained below the MPL. Possible reason for this stability in concentration of Ni is due to the quality of the industrial effluent containing low concentrations of Ni.

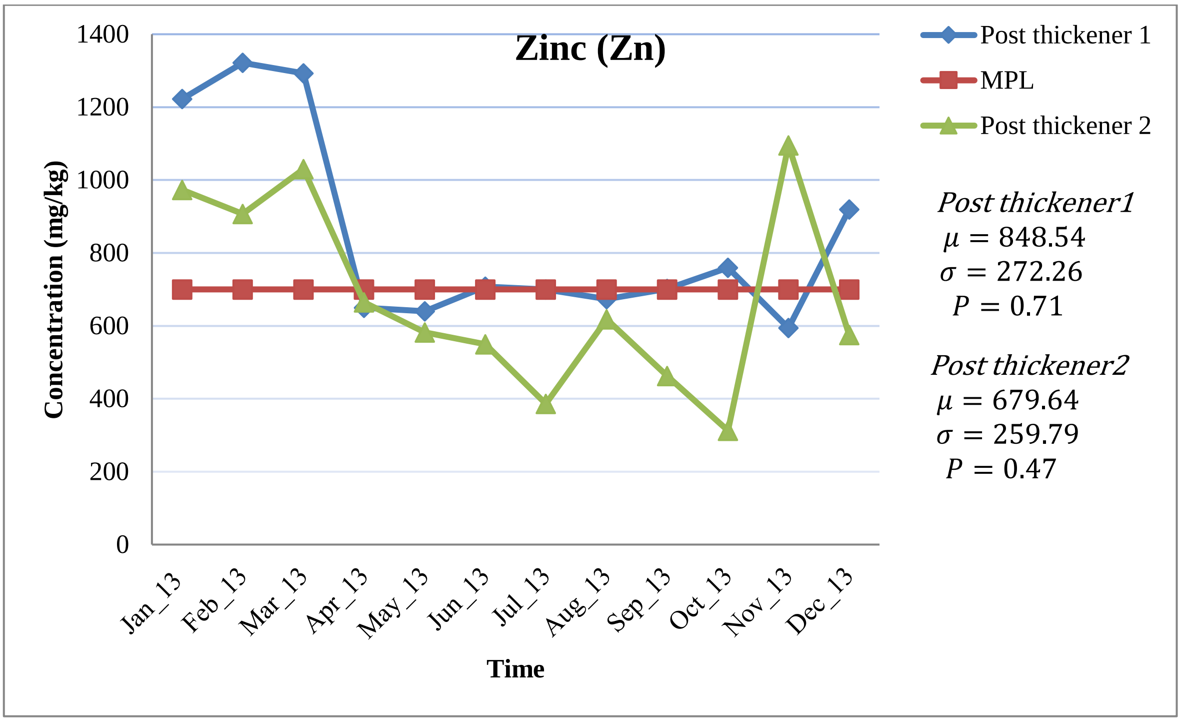


Figure 4.8: Concentration of Zn measured at post thickener 1 and post thickener 2.

The concentration of Zn was measured monthly at post thickener 1 and post thickener 2 and then plotted in figure 4.8. As can be seen from the graph above, the concentration of Zn exceeded the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater Sludge (Volume 4) during the month of Jan, Feb, Mar, Nov and December 2013. The maximum measured concentration of Zn was 1 321.6mg/kg, the minimum measured concentration was 386.2mg/kg, and an average concentration of 848.5mg/kg and 679.64mg/kg for post thickener 1 and post thickener 2 respectively. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.8

above was determined and presented in figure 4.8. The probability of exceedance of the heavy metal present in post thickener 1 and 2, is 0.71 and 0.47, respectively.

As can be seen in figure 4.8 above, the concentration of Zn present in post thickener 1 and post thickener 2 vary with time. This is as a result of variations in constituents loading in the raw wastewater. The quality of the industrial effluent that is directly discharged into the wastewater collection systems will have a direct impact on heavy metal concentration present in the raw wastewater.

It is also noted that the probability that the MPL will be exceeded is 0.71 and 0.47 for post thickener 1 and post thickener 2 respectively is of concern. The release of high amount of Zn into the receiving environment can trigger health and environmental problems. Some of the symptoms of ingestion of toxic amounts of Zn include abdominal pain, nausea and vomiting. In addition to this, effects of ingestion of toxic amounts of Zn include lethargy, anemia and dizziness (Haase et al., 2010).

The concentration of heavy metals present in the effluent from post thickener 1 were plotted together in order to see if there is any correlation between the heavy metal concentrations.

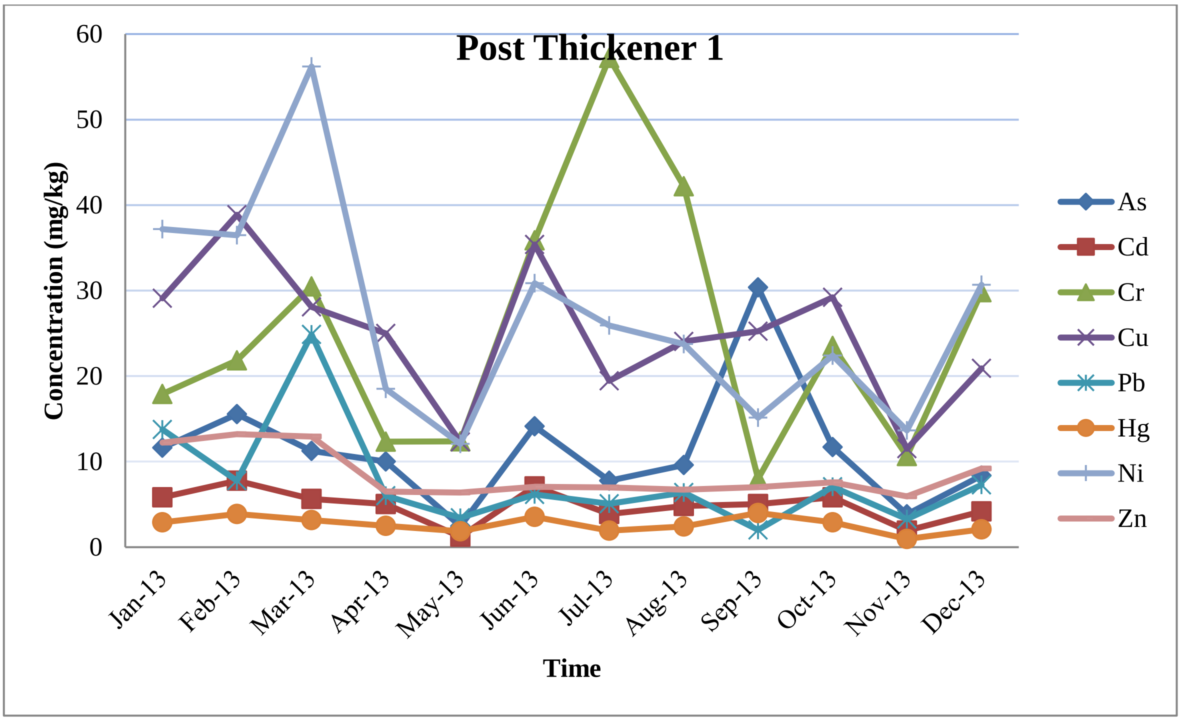


Figure 4.9: Concentration of As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn measured at post thickener 1

As can be seen on figure 4.9 above, a correlation between the following heavy metal concentration present in the effluent from post thickener 1 is evident; As and Hg; Cd and Cu; Cd and Hg; Cu and Hg; Pb and Ni; Pb and Zn; Ni and Zn. Having established that there is a correlation between a number of heavy metal concentration present in the effluent from post thickener 1, these heavy metal concentrations were plotted against each other and a correlation coefficient was determined, see figure 4.10 to 4.16 below.

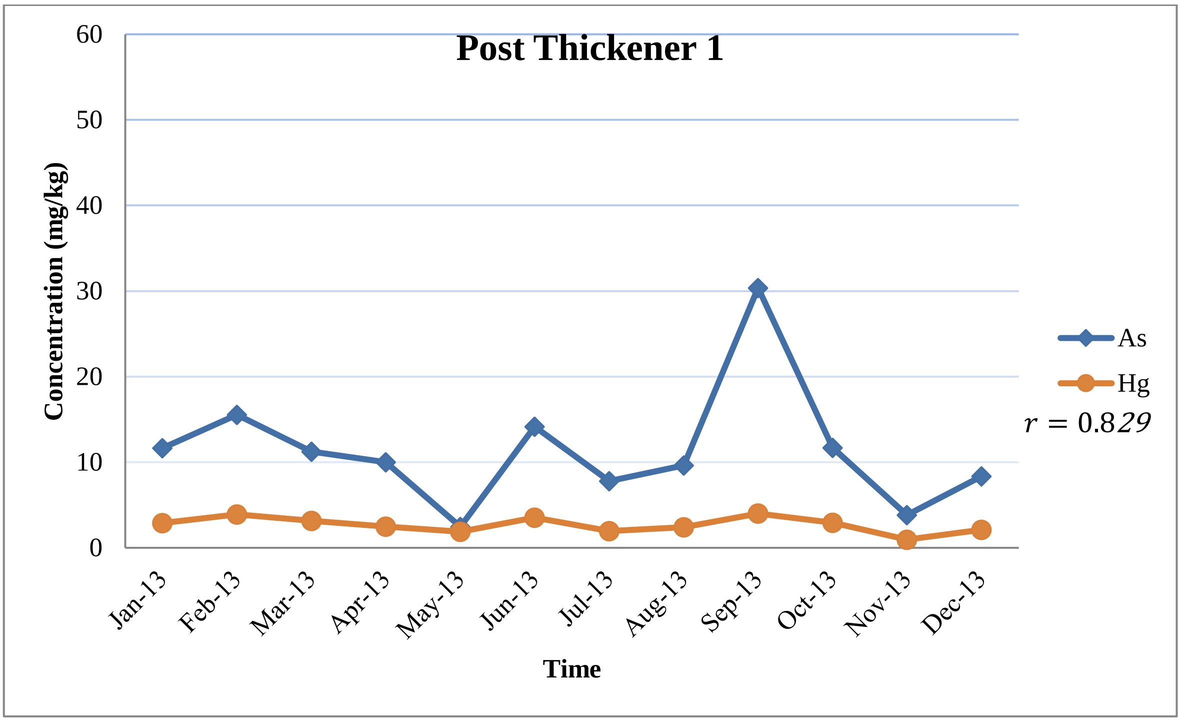


Figure 4.10: Concentration of As and Hg measured at post thickener 1.

The concentration of As and Hg present in the effluent from post thickener 1 were plotted together, see figure 4.10 above. As can be seen on figure 4.10 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 1. The correlation coefficient was determined to measure how strong the relationship is between the two heavy metal concentrations. The correlation coefficient (r) for the plot above is 0.829, indicating that a strong positive correlation exist between the concentration of As and Hg present in the effluent from post thickener 1.

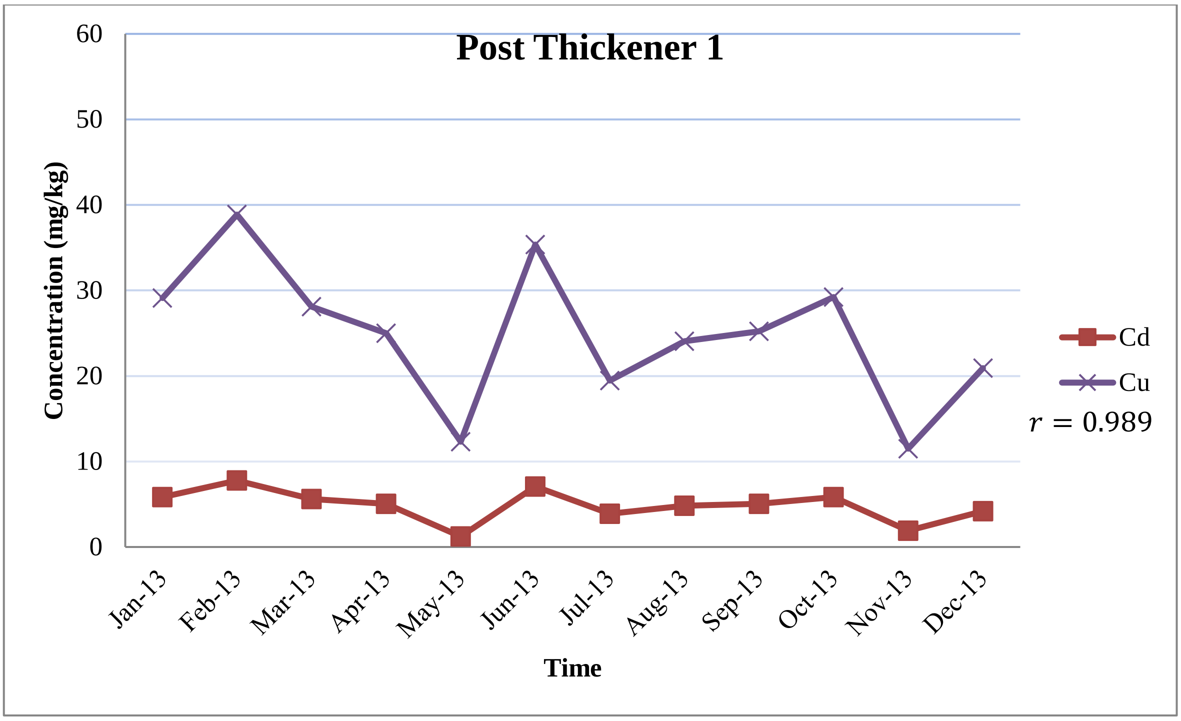


Figure 4.11: Concentration of Cd and Cu measured at post thickener 1.

The concentration of Cd and Cu present in the effluent from post thickener 1 were plotted together, see figure 4.11 above. As can be seen on figure 4.11 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 1. The correlation coefficient *(r)* for the plot above is 0.989, indicating that a strong positive correlation exists between the concentration of Cd and Cu present in the effluent from post thickener 1.

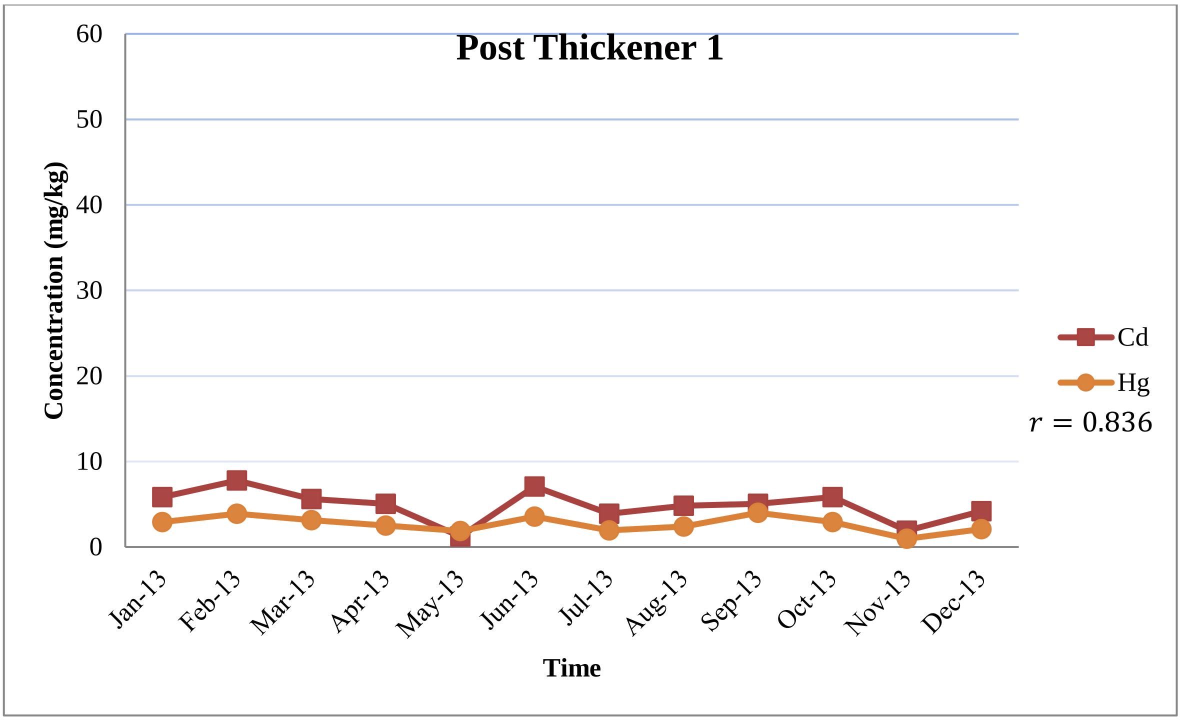


Figure 4.12: Concentration of Cd and Hg measured at post thickener 1.

The concentration of Cd and Hg present in the effluent from post thickener 1 were plotted together, see figure 4.12 above. As can be seen on figure 4.12 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 1. The correlation coefficient (*r*) for the plot above is 0.836, indicating that a positive correlation exists between the concentration of Cd and Hg present in the effluent from post thickener 1.

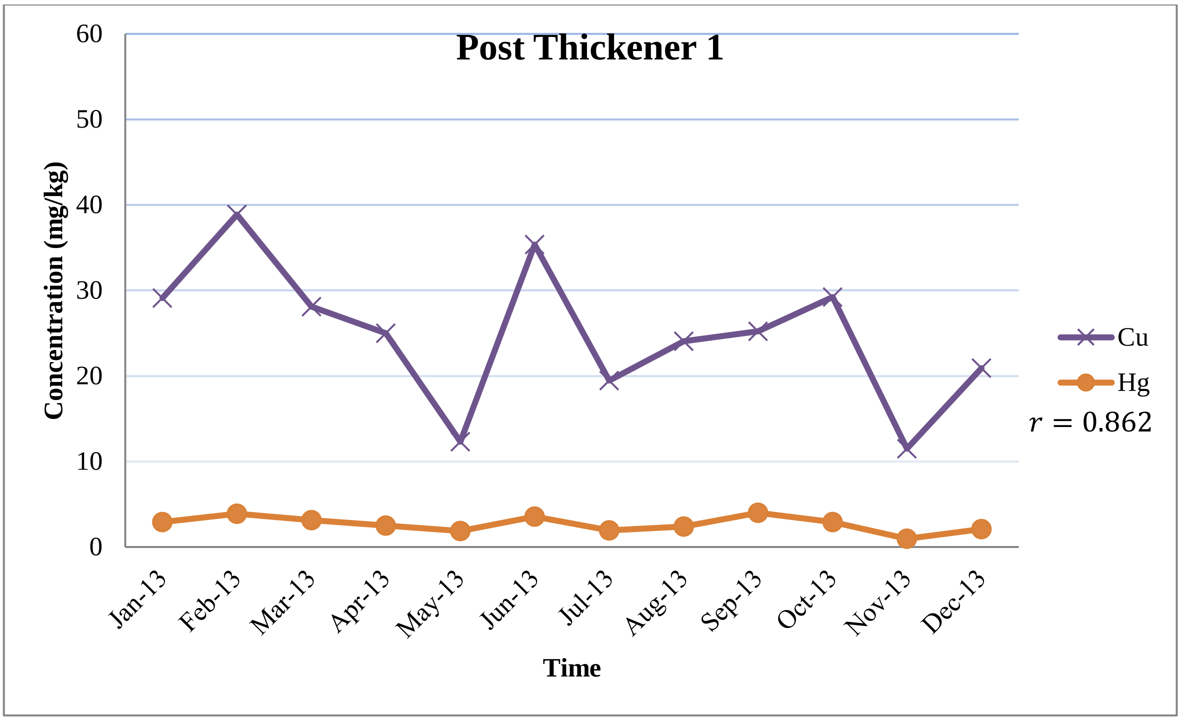


Figure 4.13: Concentration of Cu and Hg measured at post thickener 1.

The concentration of Cu and Hg present in the effluent from post thickener 1 were plotted together, see figure 4.13 above. As can be seen on figure 4.13 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 1. The correlation coefficient (*r)* for the plot above is 0.862, indicating that a positive correlation exists between the concentration of Cu and Hg present in the effluent from post thickener 1.

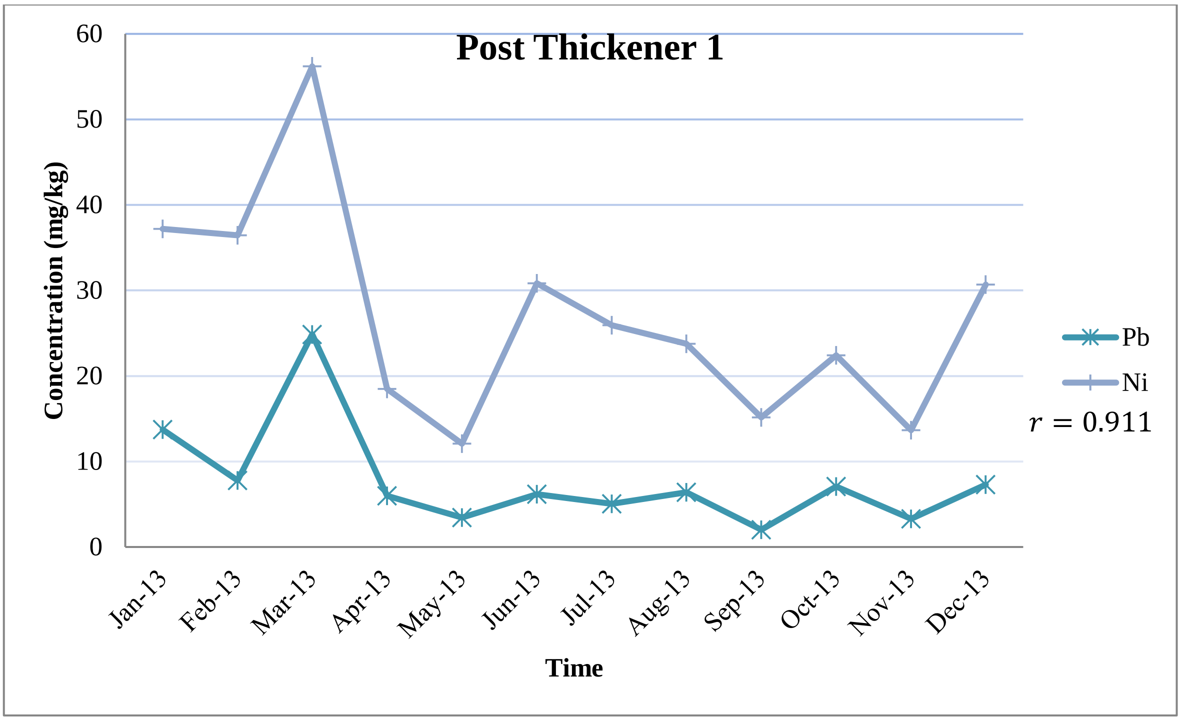


Figure 4.14: Concentration of Pb and Ni measured at post thickener 1.

The concentration of Pb and Ni present in the effluent from post thickener 1 were plotted together, see figure 4.14 above. As can be seen on figure 4.14 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 1. The correlation coefficient *(r)* for the plot above is 0.911, indicating that a strong positive correlation exists between the concentration of Pb and Ni present in the effluent from post thickener 1.

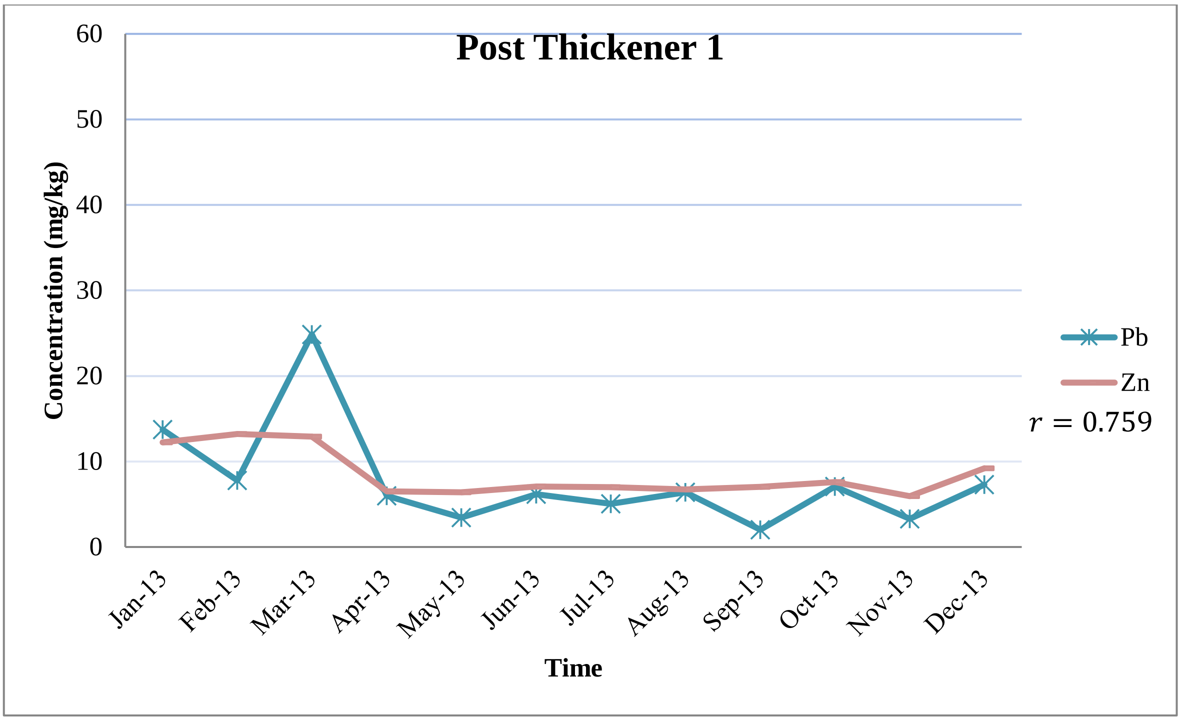


Figure 4.15: Concentration of Pb and Zn measured at post thickener 1.

The concentration of Pb and Zn present in the effluent from post thickener 1 were plotted together, see figure 4.15 above. As can be seen on figure 4.15 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 1. The correlation coefficient (*r)* for the plot above is 0.759, indicating that a positive correlation exists between the concentration of Pb and Zn present in the effluent from post thickener 1.

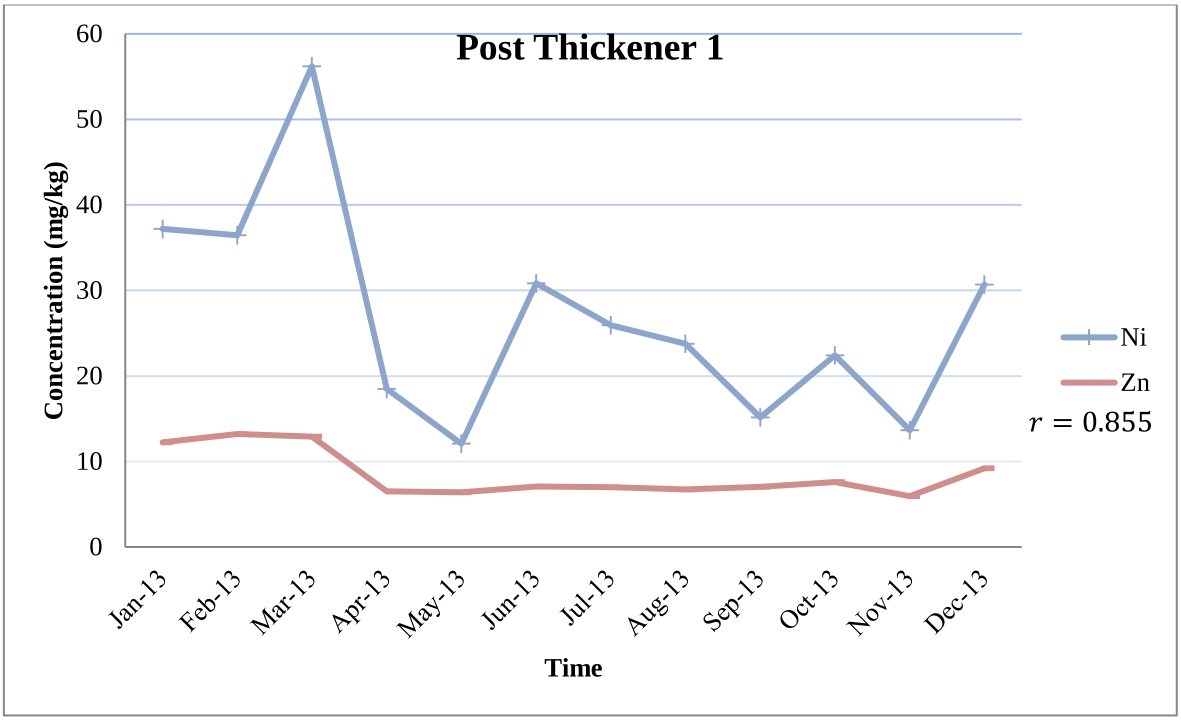


Figure 4.16: Concentration of Ni and Zn measured at post thickener 1.

The concentration of Ni and Zn present in the effluent from post thickener 1 were plotted together, see figure 4.16 above. As can be seen on figure 4.16 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 1. The correlation coefficient (*r)* for the plot above is 0.855, indicating that a positive correlation exists between the concentration of Ni and Zn present in the effluent from post thickener 1.

Having established the correlation that exists in the heavy metal concentration present in post thickener 1, the concentration of heavy metals present in the effluent from post thickener 2 were then plotted together in order to see if there is any correlation between the heavy metal concentrations, see figure 4.17 below.

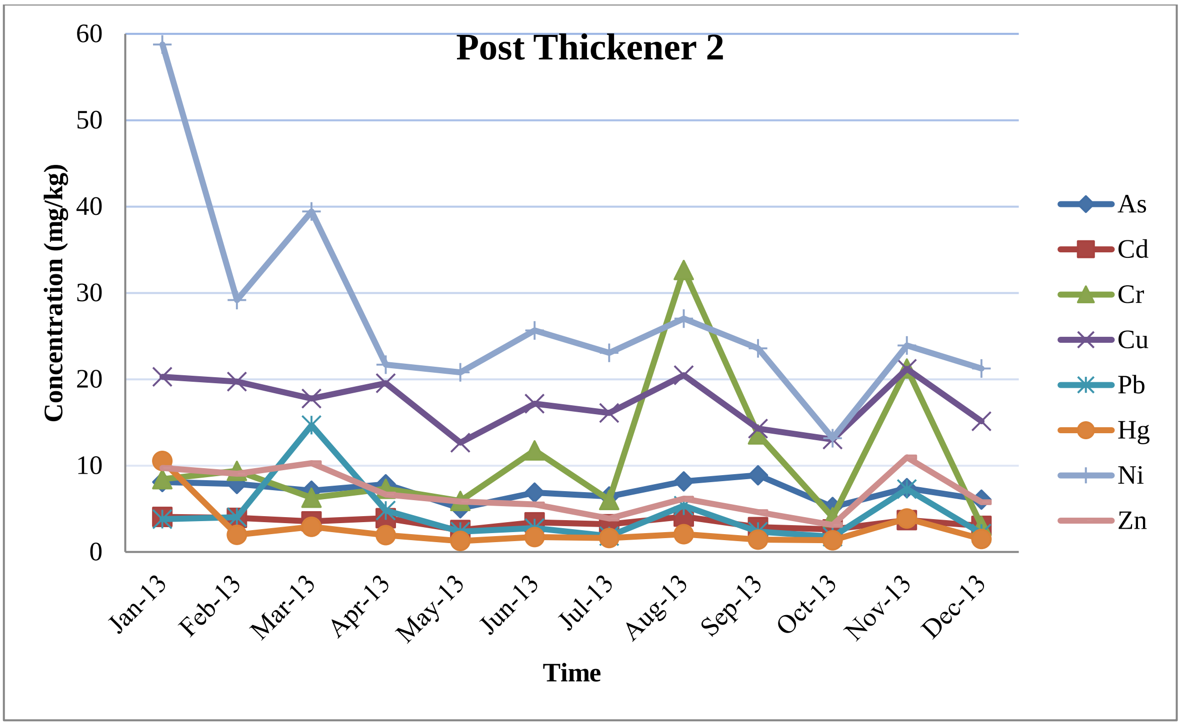


Figure 4.17: Concentration of As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn measured at post thickener 2.

As can be seen on figure 4.17 above, a correlation between the following heavy metal concentration present in the effluent from post thickener 2 is evident; Cd and Cu; Hg and Ni. Having established that there is a correlation between several heavy metal concentration present in the effluent from post thickener 2, these heavy metal concentrations were plotted against each other and a correlation coefficient was determined, see figure 4.18 and 4.19 below.

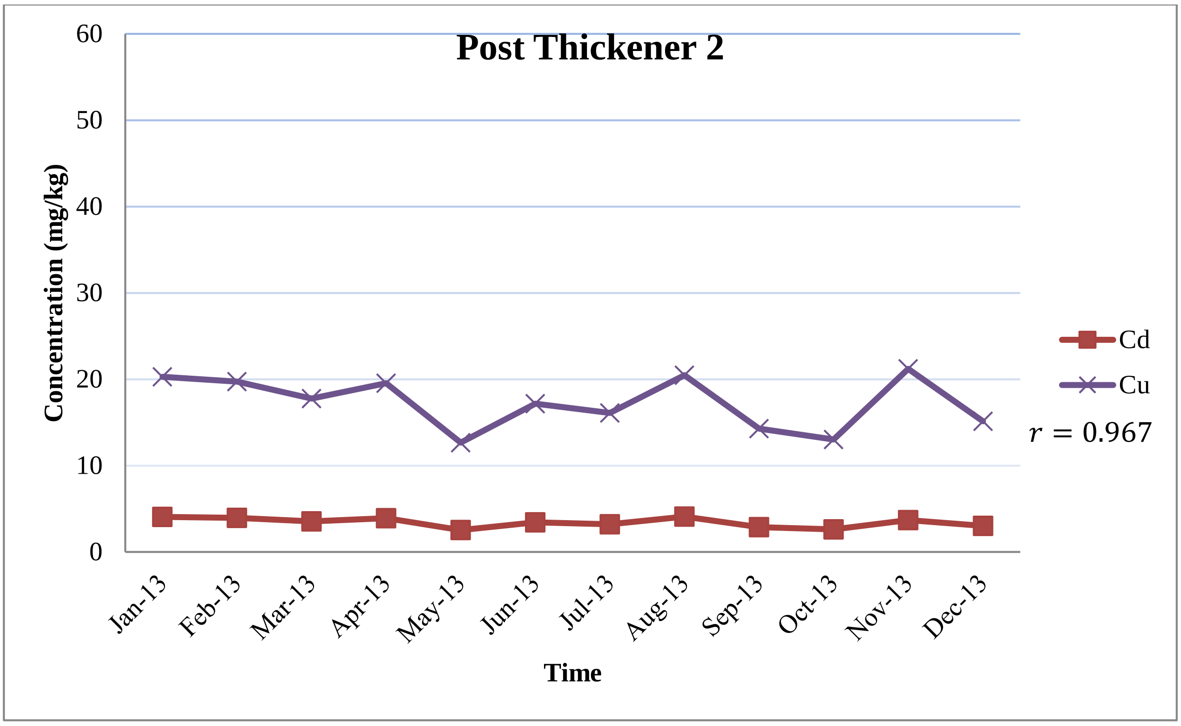


Figure 4.18: Concentration of Cd and Cu measured at post thickener 2.

The concentration of Cd and Cu present in the effluent from post thickener 2 were plotted together, see figure 4.18 above. As can be seen on figure 4.18 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 2. The correlation coefficient (*r)* for the plot above is 0.967, indicating that a strong positive correlation exists between the concentration of Cd and Cu present in the effluent from post thickener 2.

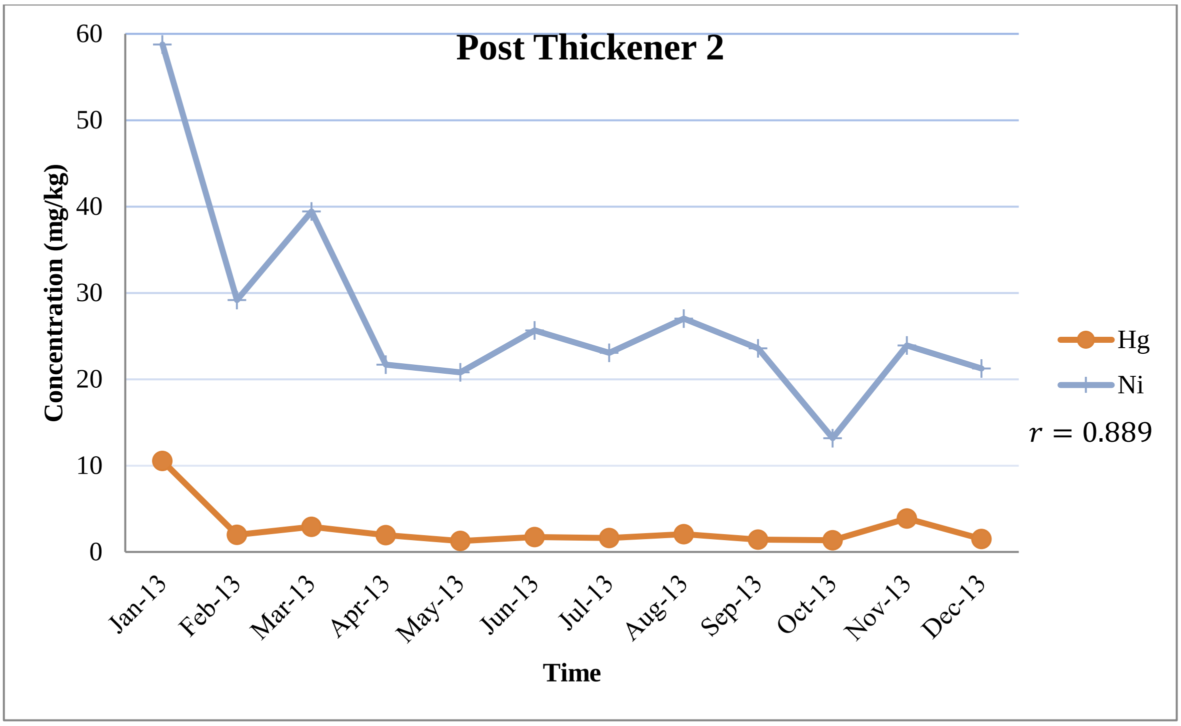


Figure 4.19: Concentration of Hg and Ni measured at post thickener 2.

The concentration of Hg and Ni present in the effluent from post thickener 2 were plotted together, see figure 4.19 above. As can be seen on figure 4.19 above a correlation exist between the two heavy metal concentration present in the effluent from post thickener 2. The correlation coefficient (*r)* for the plot above is 0.889, indicating that a positive correlation exists between the concentration of Hg and Ni present in the effluent from post thickener 2.

Having established the concentration of heavy metals present in post thickener 1 and post thickener 2, the next step was to determine the concentration of the heavy metals present in the soil of were final disposal is undertaken. Soil samples were collected from five different locations at the Darvill sludge land, soil sample 4, 9, 12, 15 and 24. Sampling and testing of the metal concentration for the Darvill sludge land soil profile (100mm, 200mm, 300mm, 400mm and 500mm) was performed once in 2013 and the results for soil samples 4, 9, 12, 15 and 24 are captured in figures 4.20 to 4.27. The different readings obtained for each sample site at various sampling depth were averaged out to give one reading and captured on the figure below. The concentration ranges presented in figures 4.20 to 4.27 are related to the MPL, i.e. 0-50%, 50-75%, and 75-99% of the MPL. The significance of the results presented in figures 4.20 to 4.27 will be discussed in more detail immediately after the presentation of table 4.3e below.

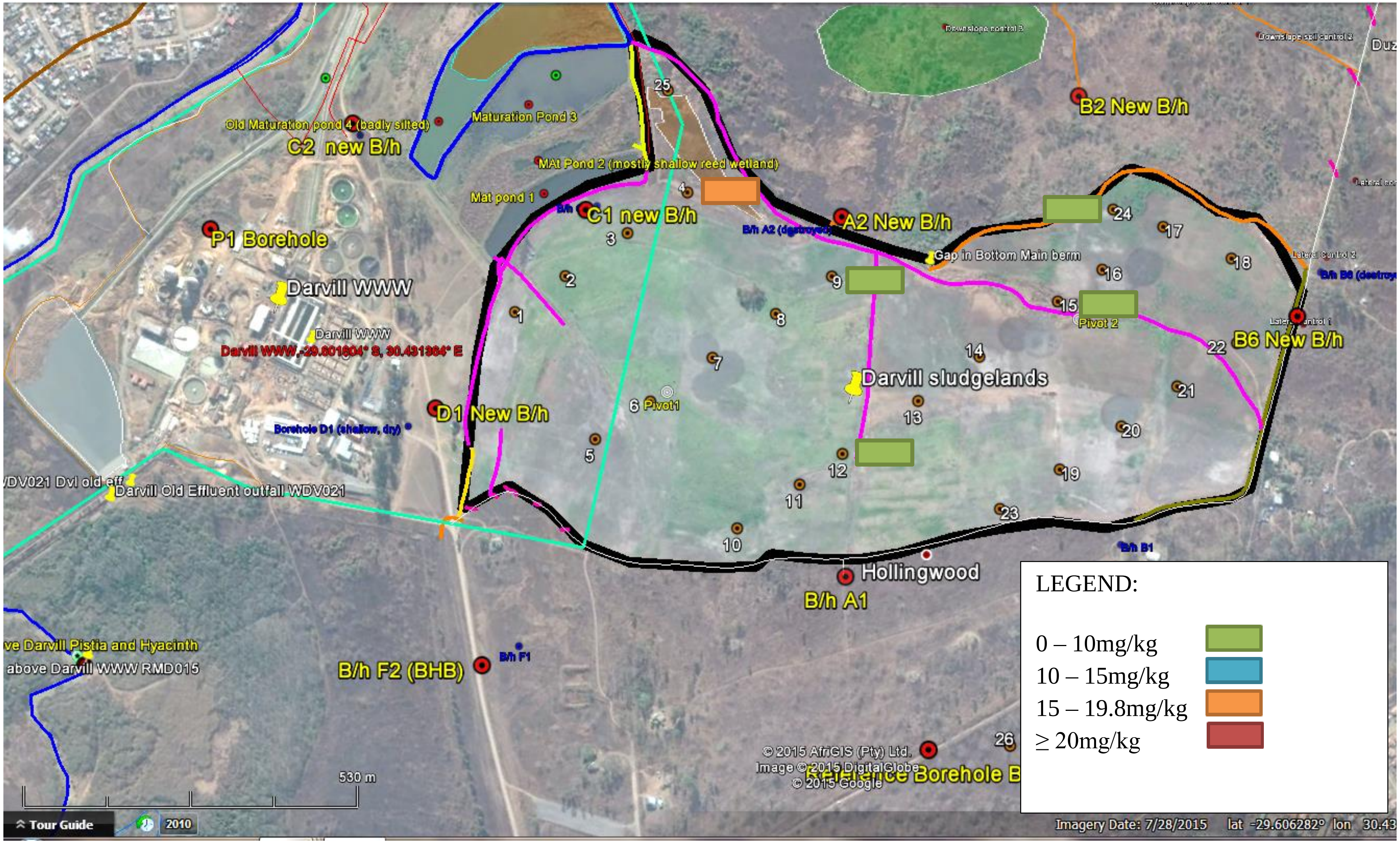


Figure 4.20: Concentration of As for soil sample 4, 9, 12, 15 and 24.

The concentrations of As measured for each sample site at various soil depth were averaged out to give one reading per sample site and then plotted in figure 4.20. As can be seen on the figure, the average concentration of As stayed below the MPL for all sample sites. The maximum measured concentration of As was 16.2mg/kg for soil sample 4 and the minimum measured concentration was 5.3mg/kg for soil sample 15.

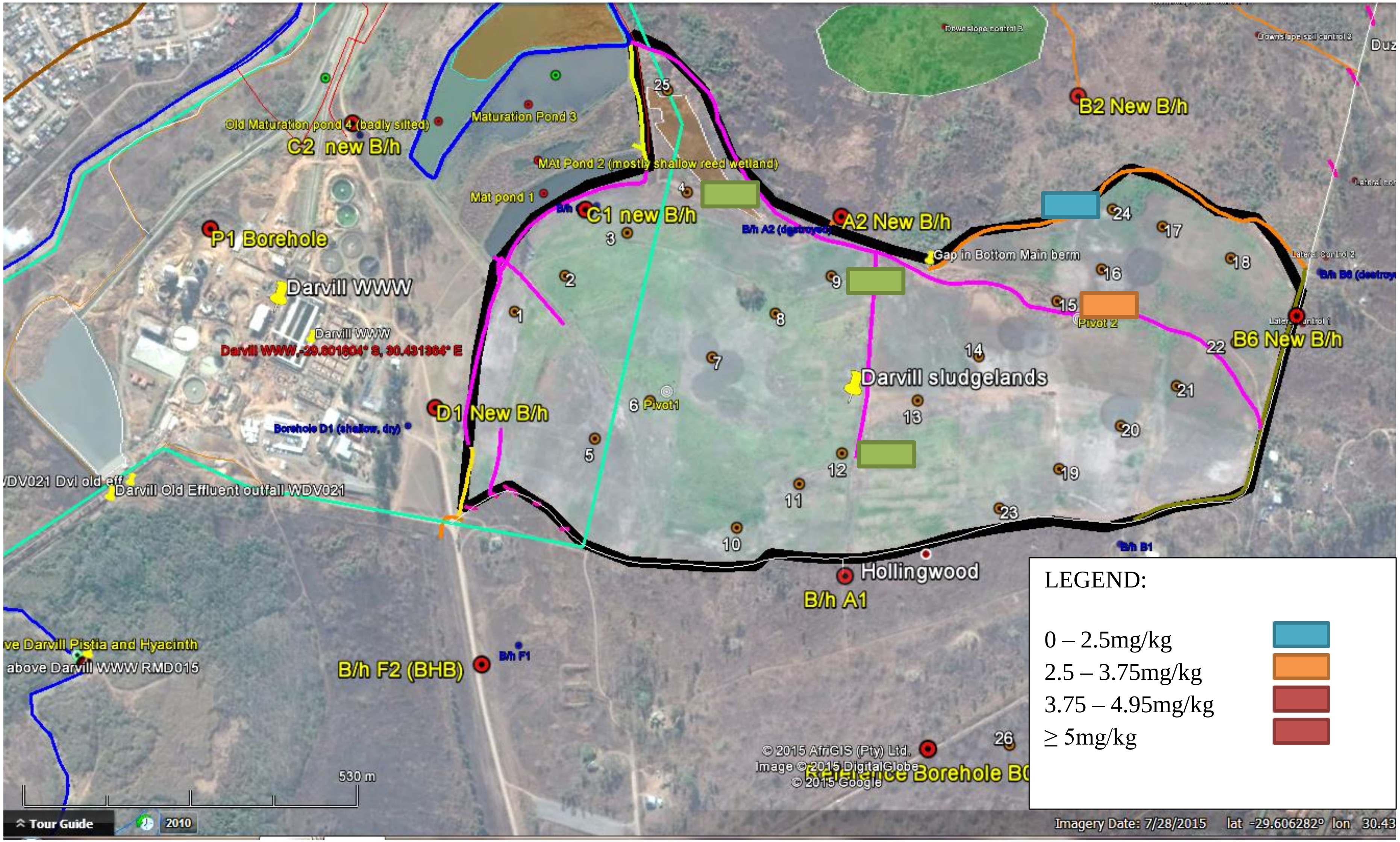


Figure 4.21: Concentration of Cd for soil sample 4, 9, 12, 15 and 24.

The concentrations of Cd measured at each sample site at various soil depths were averaged out to give one reading per sample site and then plotted in figure 4.21. As can be seen on the figure above, the average concentration of Cd stayed below the MPL for all sample sites. The maximum measured concentration of Cd was 3.9mg/kg for soil sample 15 and the minimum measured concentration was 2mg/kg for soil sample 4 and 12.

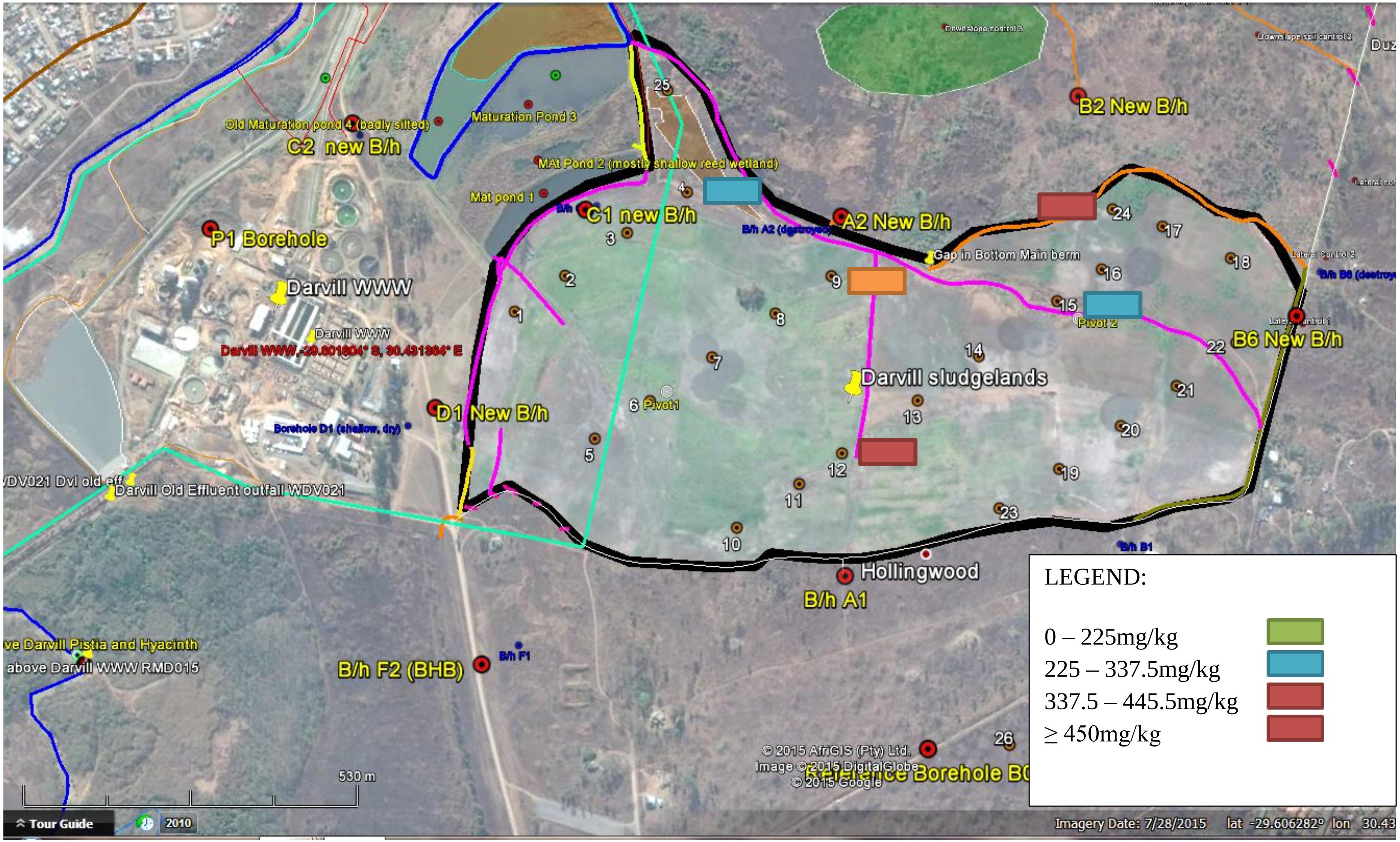


Figure 4.22: Concentration of Cr for soil sample 4, 9, 12, 15 and 24.

The concentrations of Cr measured for each sample site at various soil depths were averaged out to give one reading per sample site and then plotted in figure 4.22. As can be seen on the figure, average concentration of Cr measured at soil sample 12 and 24 exceeded the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4). The maximum measured concentration of Cr was 1 717.2mg/kg for soil sample 24 and the minimum measured concentration was 265.2mg/kg for soil sample 4.

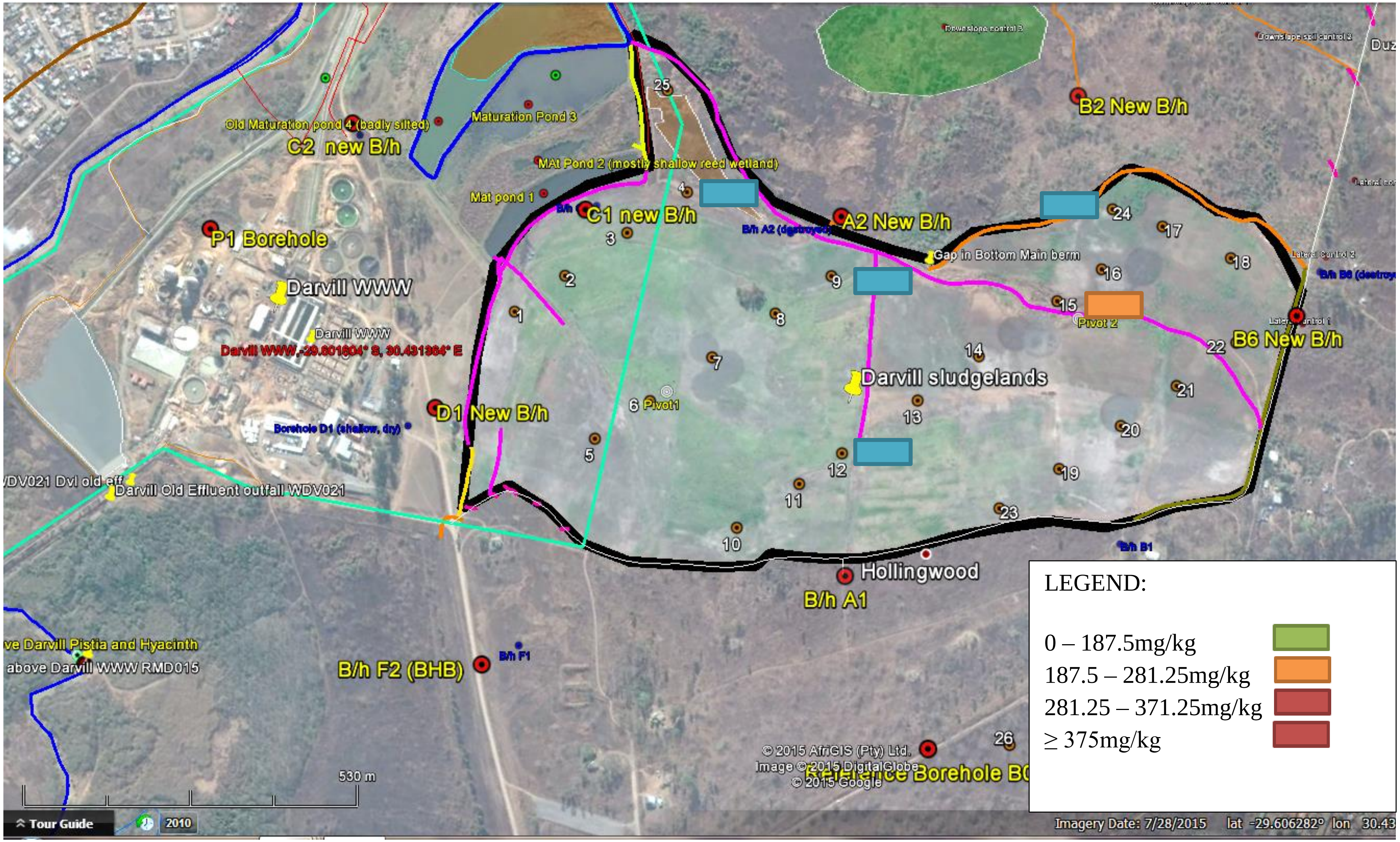


Figure 4.23: Concentration of Cu for soil sample 4, 9, 12, 15 and 24.

The concentrations of Cu measured for each sample site at various soil depths were averaged out to give one reading per sample site and then plotted in figure 4.23. As can be seen on the figure, the average concentration of Cu stayed below the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The maximum measured concentration of Cu was 295.8mg/kg for soil sample 15 and the minimum measured concentration was 200mg/kg for soil sample 4 and 12.

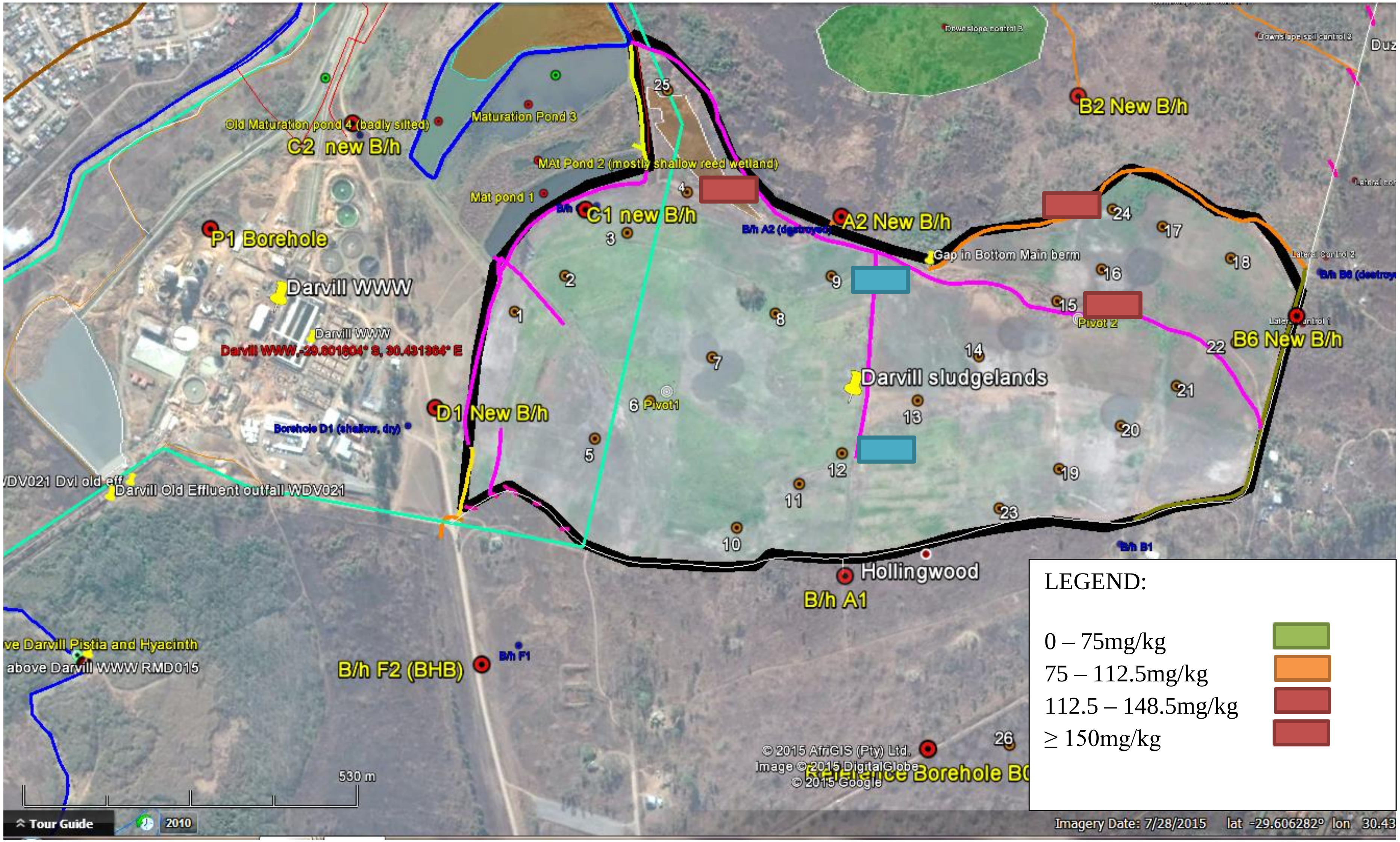


Figure 4.24: Concentration of Pb for soil sample 4, 9, 12, 15 and 24.

The concentrations of Pb measured for each sample site at various soil depths were averaged out to give one reading per sample site and then plotted in figure 4.24. As can be seen on the figure, the average concentration of Pb measured at soil sample 4, 15 and 24 exceeded the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The maximum measured concentration of Pb was 462.3mg/kg for soil sample 4 and the minimum measured concentration was 99.9mg/kg for soil sample 9.

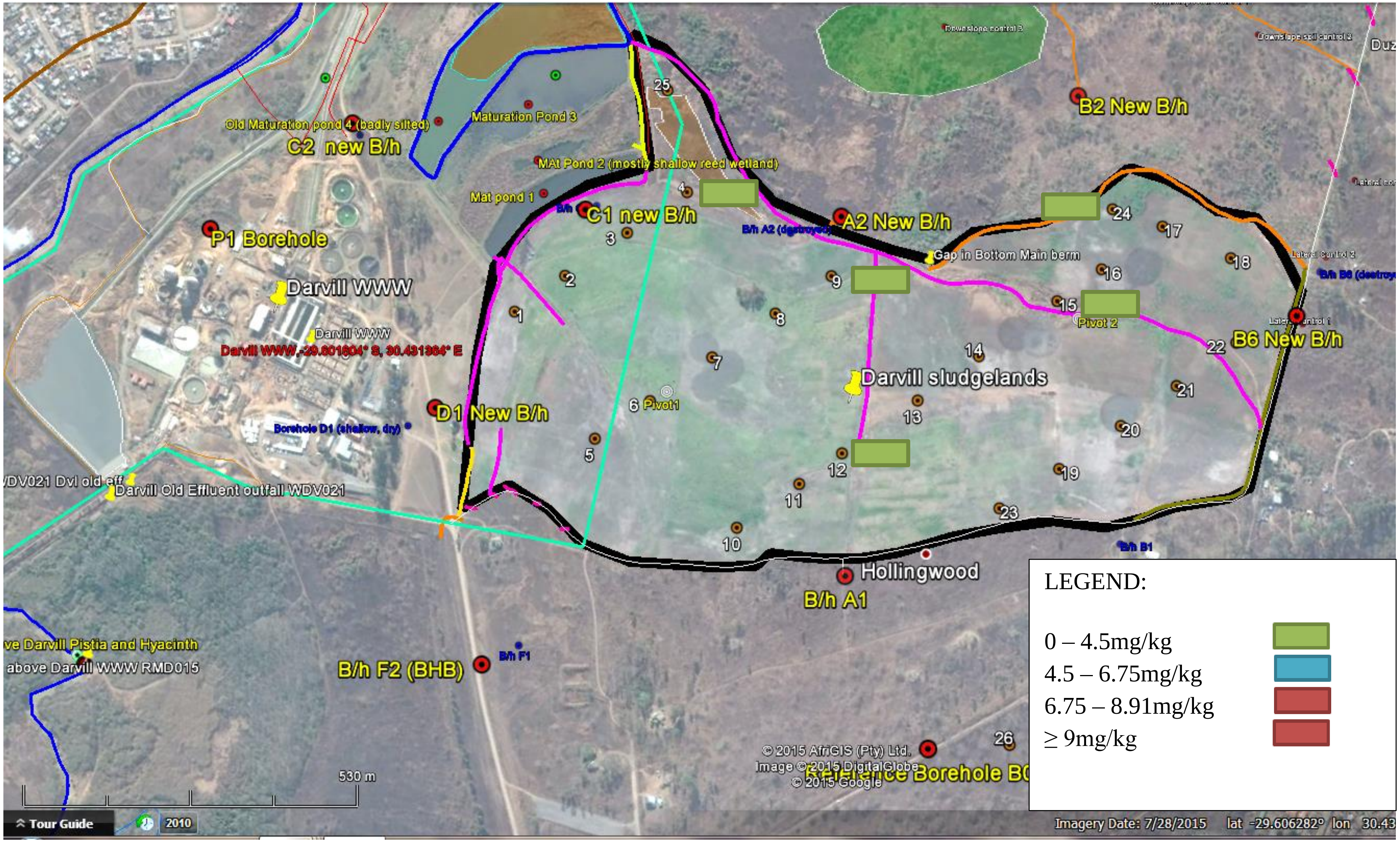


Figure 4.25: Concentration of Hg for soil sample 4, 9, 12, 15 and 24.

The concentrations of Hg measured for each sample site at various soil depths were averaged out to give one reading per sample site and then plotted in figure 4.25. As can be seen on the figure, the average concentration of Hg stayed below the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The maximum measured concentration of Hg was 4.0mg/kg for soil sample 15 and the minimum measured concentration was 1.2mg/kg for soil sample 4.

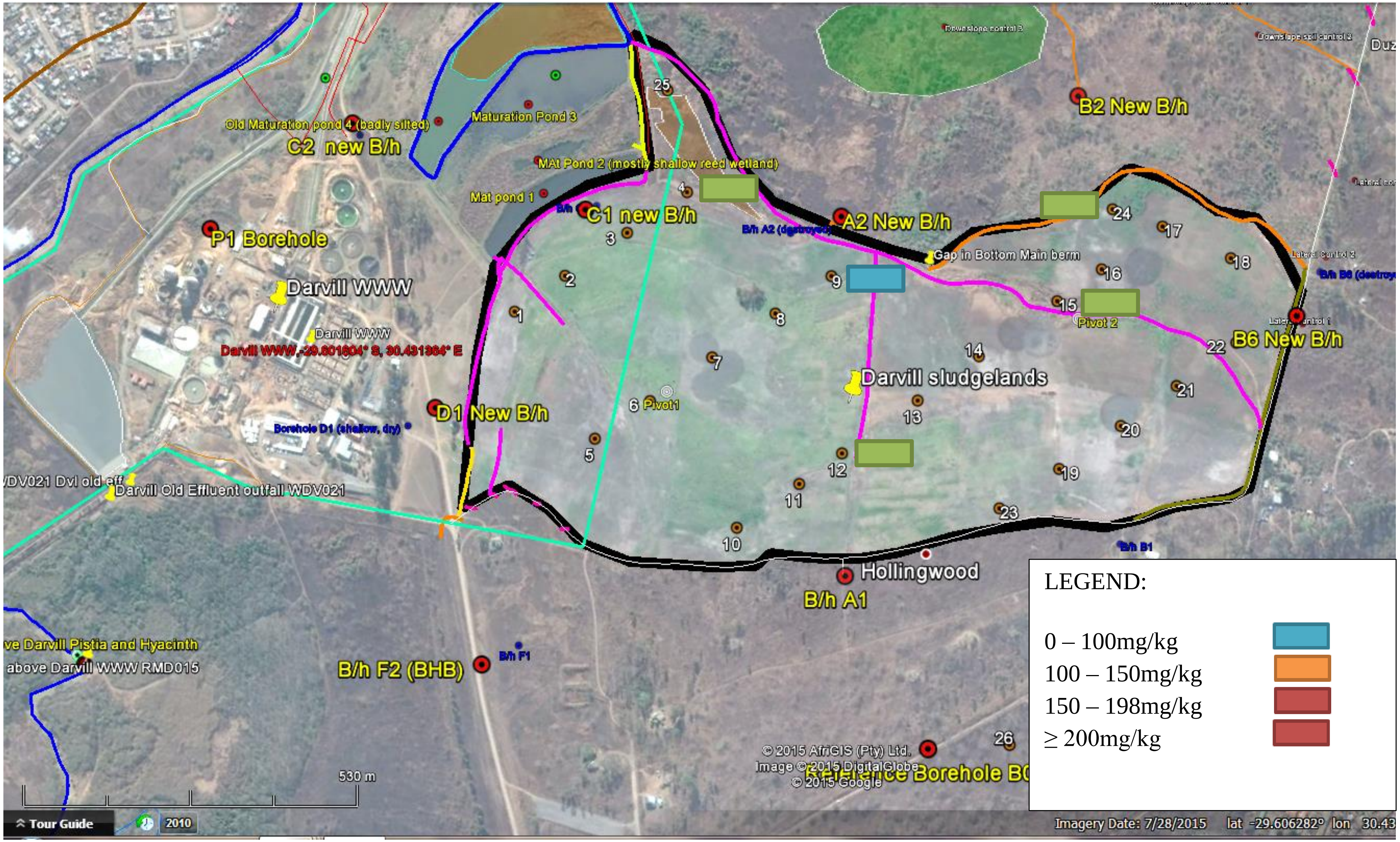


Figure 4.26: Concentration of Ni for soil sample 4, 9, 12, 15 and 24.

The concentrations of Ni measured for each sample site at various soil depths were averaged out to give one reading per sample site and then plotted in figure 4.26. As can be seen on the figure, the average concentration of Ni stayed below the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The maximum measured concentration of Ni was 147.4mg/kg for soil sample 9 and the minimum measured concentration was 18.0mg/kg for soil sample 15.

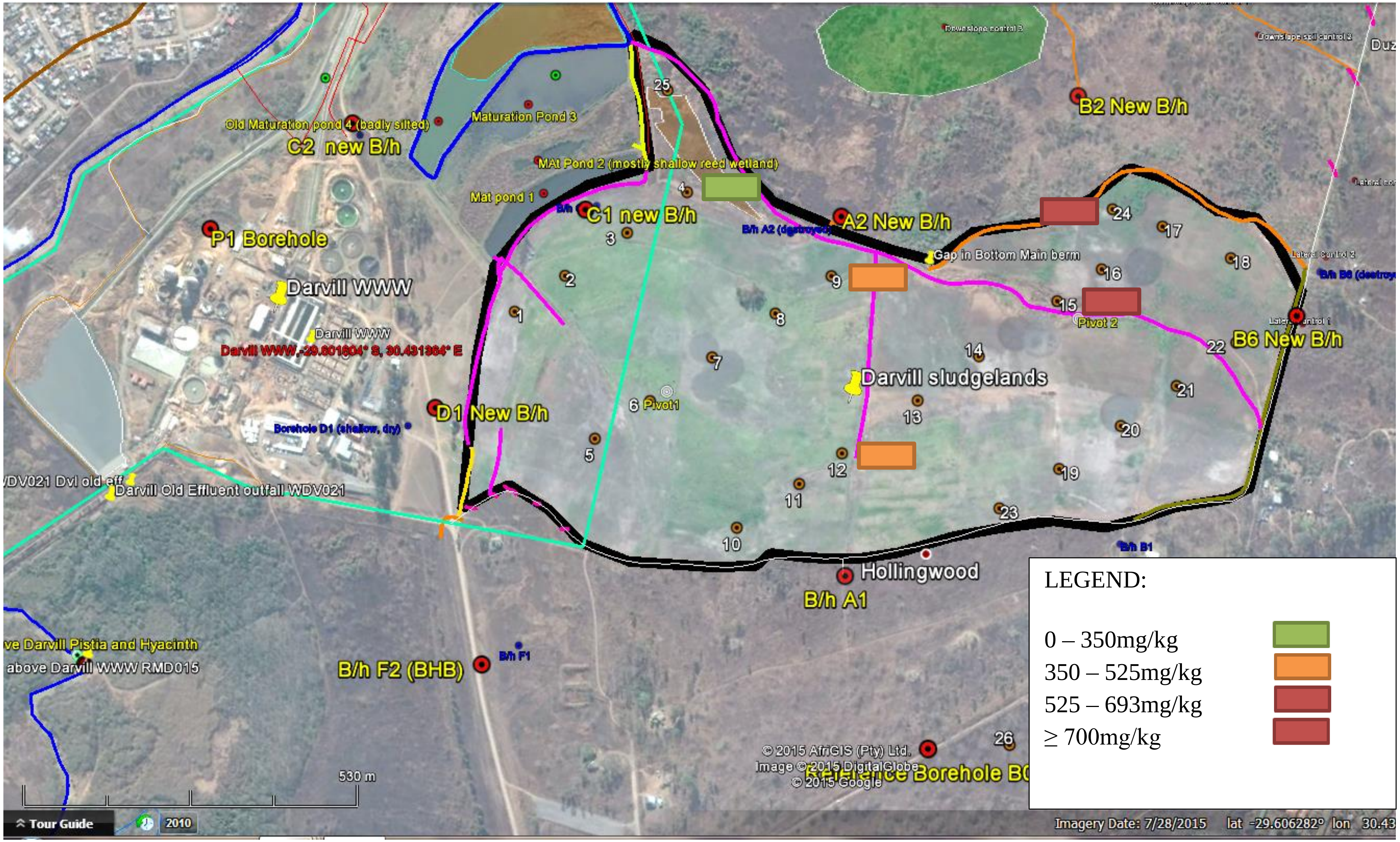


Figure 4.27: Concentration of Zn for soil sample 4, 9, 12, 15 and 24.

The concentrations of Zn measured for each sample site at various soil depths were averaged out to give one reading per sample site and then plotted in figure 4.27. As can be seen on the figure, the average concentration of Zn measured at soil sample 15 and 24 exceeded the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The maximum measured concentration of Zn was 1 338.2mg/kg for soil sample 15 and the minimum measured concentration was 225.2mg/kg for soil sample 4.

The MPL of heavy metals for soils receiving high sludge loading rates is as per the guidelines for utilisation and disposal of wastewater sludge (volume 4); see table 4.2. The MPL put in place for metals present in receiving soil is intended to ensure that the quality of soil does not degrade to a point where remediation becomes necessary (Herselman & Snyman, 2006).

Table 4.2: Maximum permissible level for soil receiving high sludge loading rates.

ELEMENT	**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

The average concentration of heavy metal present in the soil was compared to the MPL for each soil sample in order to assess whether it is still acceptable to dispose sludge at the Darvill sludge land. In cases where the concentration of heavy metals present in the soil exceeds the MPL, it has been recommended sludge cannot be discharged on the Darvill sludge land in order to ensure that the quality of soil does not degrade to a point where remediation becomes necessary.

In cases where the concentration of heavy metals present in the soil does not exceed the MPL, the permissible application rate (PAR) of the sludge was calculated. This is to ensure that the metal content of the soil will not increase to a level above the MPL. The PAR is calculated using the following equation as per the guidelines for utilisation and disposal of wastewater sludge (volume 4):

$$PAR = \frac{TMT - Soil_{conc}}{Sludge_{conc}} \times 3900$$

Where: PAR = permissible application rate (ton/ha)

TMT = Total maximum threshold (mg/kg)

$\text{Soil}_{\text{conc}}$ = the actual metal content of the solid (mg/kg)

$\text{Sludge}_{\text{conc}}$ = metal concentration in the sludge that will be applied (mg/kg)

3900 = conversion factor to account for soil density (1.3g/cm3) and sludge incorporation depth of 300mm.

The results obtained for each sample location are captured in the table below. It has been noted that the PAR of sludge increases with a decrease in the concentration of the heavy metals present in the soil.

Table 4.3a: Permissible application rate for soil sample 4.

Elements	Average conc. in soil (mg/kg)	Sludge conc. (mg/kg)	Sludge conc. (mg/l)	MPL (mg/kg)	PAR (ton/ha)	RECOMMENDATION
As	16.20	9.24	0.002	20	1605.87	**OK can discharge sludge on land**
Cd	2.00	4.13	0.001	5	2831.50	**OK can discharge sludge on land**
Cr	265.20	1799.72	0.448	450	400.46	**OK can discharge sludge on land**
Cu	200.00	211.01	0.053	375	3234.51	**OK can discharge sludge on land**
Pb	462.32	60.92	0.014	150	-	**FAILS cannot discharge sludge on land**
Hg	1.20	2.68	0.001	9	11345.72	**OK can discharge sludge on land**
Ni	69.88	27.10	0.007	200	18725.76	**OK can discharge sludge on land**
Zn	225.20	764.09	0.202	700	2423.43	**OK can discharge sludge on land**

Table 4.3b: Permissible application rate for soil sample 9.

Elements	Average conc. in soil (mg/kg)	Sludge conc. (mg/kg)	Sludge conc. (mg/l)	MPL (mg/kg)	PAR (ton/ha)	RECOMMENDATION
As	6.48	9.24	0.002	20	5707.52	**OK can discharge sludge on land**
Cd	2.00	4.13	0.001	5	2831.50	**OK can discharge sludge on land**
Cr	377.60	1799.72	0.448	450	156.89	**OK can discharge sludge on land**
Cu	215.60	211.01	0.053	375	2946.17	**OK can discharge sludge on land**
Pb	99.86	60.92	0.014	150	3209.68	**OK can discharge sludge on land**
Hg	1.84	2.68	0.001	9	10406.30	**OK can discharge sludge on land**
Ni	147.43	27.10	0.007	200	7565.14	**OK can discharge sludge on land**
Zn	548.60	764.09	0.202	700	772.76	**OK can discharge sludge on land**

Table 4.3c: Permissible application rate for soil sample 12.

Elements	Average conc. in soil (mg/kg)	Sludge conc. (mg/kg)	Sludge conc. (mg/l)	MPL (mg/kg)	PAR (ton/ha)	RECOMMENDATION
As	9.10	9.24	0.002	20	4599.79	**OK can discharge sludge on land**
Cd	2.18	4.13	0.001	5	2663.50	**OK can discharge sludge on land**
Cr	489.94	1799.72	0.448	450	-	**FAILS cannot discharge sludge on land**
Cu	215.40	211.01	0.053	375	2949.87	**OK can discharge sludge on land**
Pb	109.02	60.92	0.014	150	2623.31	**OK can discharge sludge on land**
Hg	2.04	2.68	0.001	9	10124.19	**OK can discharge sludge on land**
Ni	63.64	27.10	0.007	200	19623.48	**OK can discharge sludge on land**
Zn	613.00	764.09	0.202	700	444.06	**OK can discharge sludge on land**

Table 4.3d: Permissible application rate for soil sample 15.

Elements	Average conc. in soil (mg/kg)	Sludge conc. (mg/kg)	Sludge conc. (mg/l)	MPL (mg/kg)	PAR (ton/ha)	RECOMMENDATION
As	5.25	9.24	0.002	20	6225.93	**OK can discharge sludge on land**
Cd	3.90	4.13	0.001	5	1038.22	**OK can discharge sludge on land**
Cr	326.20	1799.72	0.448	450	268.28	**OK can discharge sludge on land**
Cu	295.80	211.01	0.053	375	1463.85	**OK can discharge sludge on land**
Pb	175.20	60.92	0.014	150	-	**FAILS cannot discharge sludge on land**
Hg	3.99	2.68	0.001	9	7279.76	**OK can discharge sludge on land**
Ni	17.96	27.10	0.007	200	26198.21	**OK can discharge sludge on land**
Zn	1338.20	764.09	0.202	700	-	**FAILS cannot discharge sludge on land**

Table 4.3e: Permissible application rate for soil sample 24.

Elements	Average conc. in soil (mg/kg)	Sludge conc. (mg/kg)	Sludge conc. (mg/l)	MPL (mg/kg)	PAR (ton/ha)	RECOMMENDATION
As	5.71	9.24	0.002	20	6031.74	**OK can discharge sludge on land**
Cd	2.86	4.13	0.001	5	2019.80	**OK can discharge sludge on land**
Cr	1717.20	1799.72	0.448	450	-	**FAILS cannot discharge sludge on land**
Cu	264.60	211.01	0.053	375	2040.51	**OK can discharge sludge on land**
Pb	173.02	60.92	0.014	150	-	**FAILS cannot discharge sludge on land**
Hg	3.42	2.68	0.001	9	8111.56	**OK can discharge sludge on land**
Ni	90.26	27.10	0.007	200	15792.84	**OK can discharge sludge on land**
Zn	871.80	764.09	0.202	700	-	**FAILS cannot discharge sludge on land**

The average concentration of heavy metals present in the soil for most of the sample locations was less than the MPL. Cr, Pb and Zn are heavy metals of concern since the average concentration present in soil exceeds the MPL. Soil samples 15 and 24 had more than one heavy metal with a concentration which exceeded the MPL. Both these sampling sites are located on the eastern portion of the Darvill sludge land which indicates that the area could potentially be unsuitable for beneficial use. The concentration of Pb for soil sample 4, which is located closest to the Msunduzi River, exceeded the MPL.

It is noted that the concentration of heavy metals present in the soil varies from one sample site to another. This is as a result of continuous application of sludge which varies in quality. As mentioned earlier in the report the main sources of heavy metals in wastewater are stormwater runoff, soil erosion and the discharge of industrial waste directly into wastewater collection systems. It is also noted that the concentration of some heavy metals present in the soil exceeds the MPL and this can be as a result of the quality of the incoming wastewater as well as the continuous application of sludge at the sludge land without rehabilitation. It should be noted that the significance of the results will be further discussed in more detail later in the report.

It is also noted that the concentration of As measured at post thickener 1 and post thickener 2 stayed below the MPL as required by the Guidelines for Utilisation and Disposal of Wastewater Sludge (Volume 4), see figure 4.1 above. The average concentration of As measured for each of the five sample sites stayed below the MPL, see figure 4.20 above.

The concentration of Cd measured at post thickener 2 stayed below the MPL, whilst the concentration of Cd measured at post thickener 1 exceeded the MPL on five occasions, see figure 4.2 above. However, the average concentration of Cd measured for each of the five sample sites stayed below the MPL, see figure 4.21 above.

The concentration of Cr measured at post thickener 1 and post thickener 2 exceed the MPL, see figure 4.3 above. The average concentration of Cr present in the soil exceed the MPL for two out of the five sample sites, see figure 4.22 above.

The concentration of Cu measured at post thickener 1 and post thickener 2 stayed below the MPL, see figure 4.4 above. It is also noted that the average concentration of Cu present in the soil stayed below the MPL for each of the five sample sites, see figure 4.23 above.

The concentration of Pb measured at post thickener 1 and post thickener 2 stayed below the MPL, see figure 4.5 above. On the contrary, the measured average concentration of Pb present in the soil exceed the MPL for three out of the five sample sites, see figure 4.24 above.

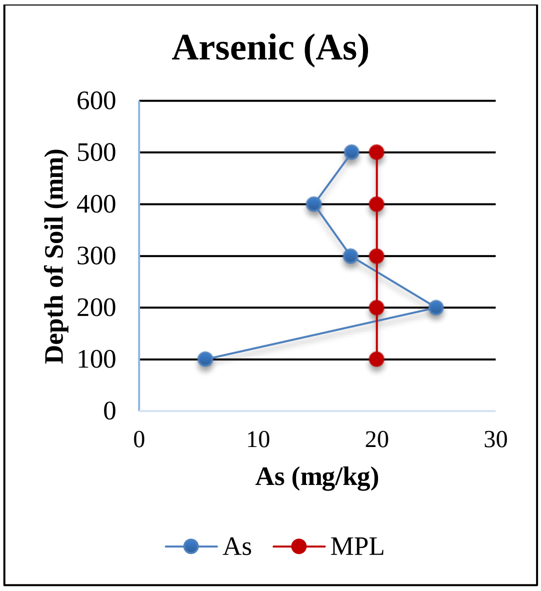
The concentration of Hg measured at post thickener 1 and post thickener 2 stayed below the MPL, see figure 4.6 above. The average concentration of Hg measured for each of the five sample sites stayed below the MPL, see figure 4.25 above.

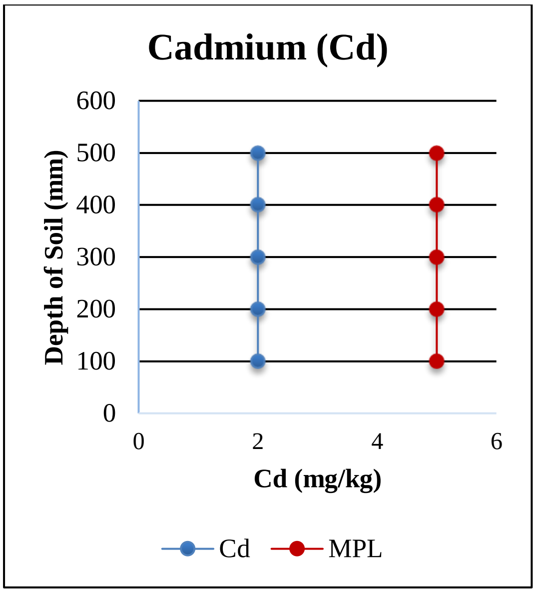
The concentration of Ni measured at post thickener 1 and post thickener 2 stayed below the MPL, see figure 4. 7 above. The average concentration of Ni measured for each of the five sample sites stayed below the MPL, see figure 4.26 above.

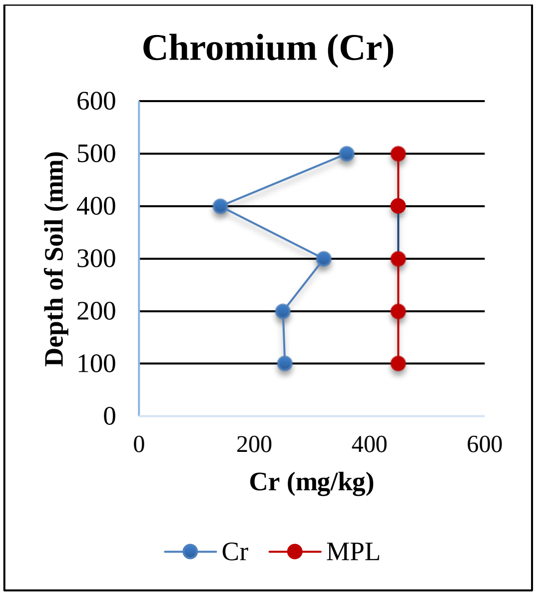
The concentration of Zn present in post thickener 1 and post thickener 2 exceeded the MPL during the month of Jan, Feb, Mar, Nov and Dec 2013, see figure 4.7 above. The average concentration of Zn present in the soil exceed the MPL for two out of the five sample sites, see figure 4.27 above.

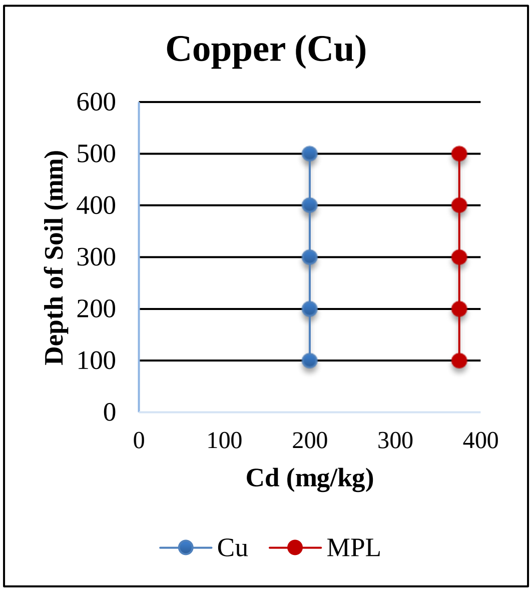
The PAR of each element which was tested is dependent on the average concentration of heavy metals present in soil. For elements with low concentrations present in the soil sampled, the PAR calculated was high, and the PAR decreased with an increase in heavy metal concentration present at the sampling site.

Below is a graphic representation of the heavy metal concentration present in the Darvill sludge land soil profile as measured in 2013 for soil sample 4 (refer to annexure B for soil sample 9, 12, 15 and 24 graphic representation). It can be seen from the graphs below that the concentration of As and Pb exceed the MPL in the top 200mm of the soil profile.


Arsenic (As)
Depth of Soil (mm)
600
500
400
300
200
100
0
0
10
20
30
As (mg/kg)
As
MPL


Cadmium (Cd)
Depth of Soil (mm)
600
500
400
300
200
100
0
0
2
4
6
Cd (mg/kg)
Cd
MPL


Chromium (Cr)
Depth of Soil (mm)
600
500
400
300
200
100
0
0
200
400
600
Cr (mg/kg)
Cr
MPL


Copper (Cu)
Depth of Soil (mm)
600
500
400
300
200
100
0
0
100
200
300
400
Cd (mg/kg)
Cu
MPL

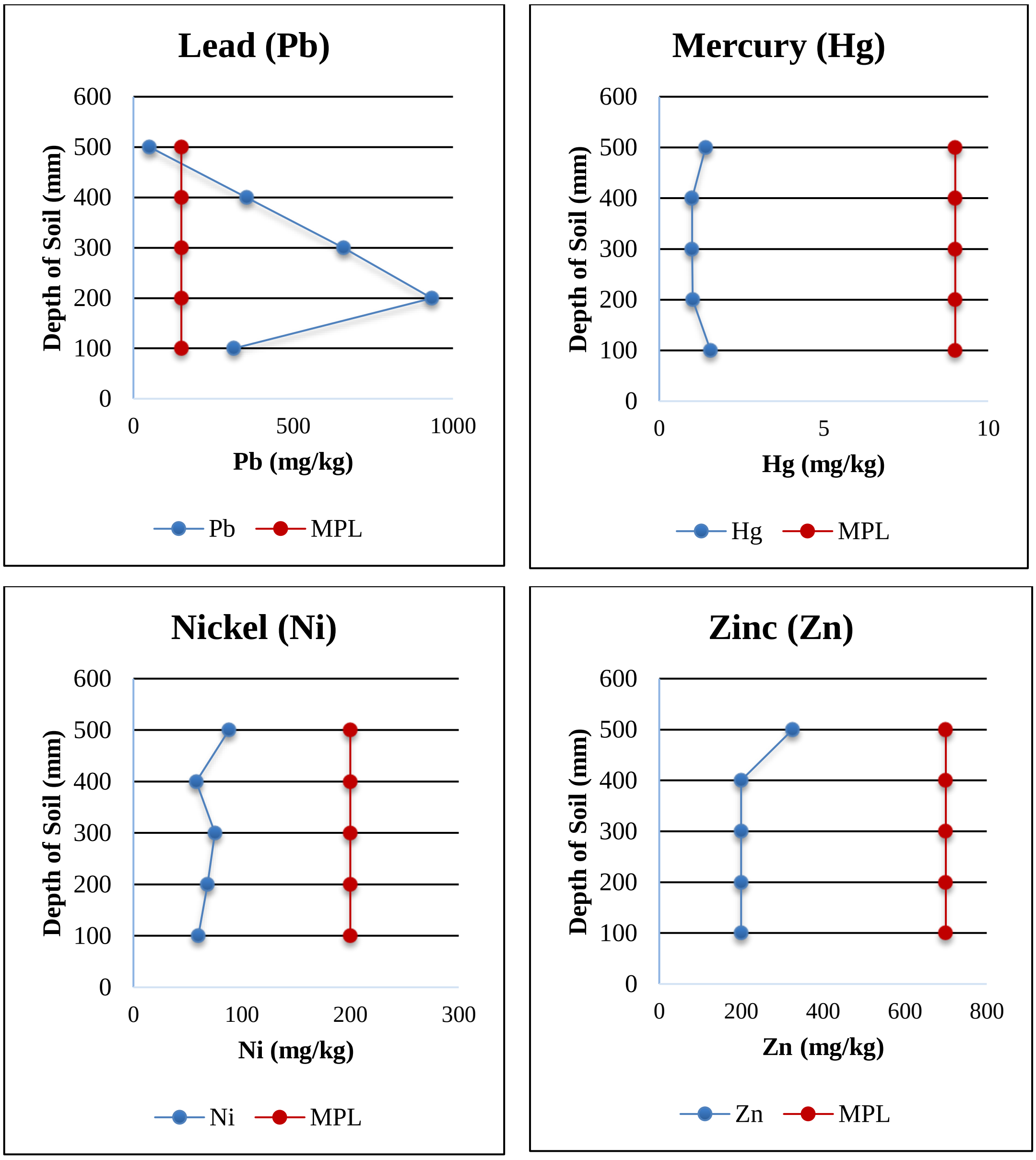


Figure 4.28: Heavy metal concentration for soil sample 4.

Having established the current levels of heavy metals in the Darvill sludge land, a model to predict future concentrations of heavy metals was created. The model created has soil moisture content and the soil bulk density as inputs. The first step in the model was to determine the amount of solute retained when disposal of the sludge takes place at the Darvill sludge land using the following equation:

$$\rho_b \, {}^{\partial S}/_{\partial t} = k_f \theta C - k_b \rho S \qquad (1)$$

Where: ρ_b = soil bulk density (kg/m^3)

S = amount of solute retained (mg/kg)

k_f = forward reaction rate coefficient (h^{-1})

k_b = backward reaction rate coefficient (h^{-1})

θ = soil moisture content (m^3/m^3)

c = solute concentration in solution (mg/l).

For $t \rightarrow \infty$ (rate of retention approaches zero), equation (1) above yields:

$$S = \left(\theta/\rho_b\right) . k_f/k_b \, . C = K_d C \text{ (mg/kg)} \tag{2}$$

Where: $K_d = (\theta k_f / \rho_b k_b)$ (m^3/kg). distribution coefficient.

Soil moisture content and soil bulk density

The soil moisture content and soil bulk density were required to determine the amount of solute that is retained by soil when sludge is disposed at the Darvill sludge land. These were determined for each sample location at various depths (100-150mm, 300-350mm and 500-550mm) using equation 3, 4 and 5 below. Equation (3) was used to calculate the soil moisture content as a percentage of dry soil mass whilst equation (4) was used to calculate the soil moisture content as percentage of soil volume, with the latter being used to determine the amount of solute retained by soil when sludge is disposed at the Darvill sludge land. It is noted that the amount of solute not retained by the soil will migrate or decay within the soil. The migration of solute within the soil is of concern as this may result in the contamination of the groundwater.

$$\theta = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100\% \tag{3}$$

where: $\theta(\%)$ = soil moisture content (%)

W_{wet} = soil wet weight (kg)

W_{dry} = soil dry weight (kg)

$$\theta = \frac{W_{wet} - W_{dry}}{\rho_w \times V_{core}} \tag{4}$$

where: $\theta(m^3/m^3)$ = soil moisture content (m^3/m^3)

ρ_w = density of water (kg/m^3)

V_{core} = core volume (m^3)

$$\rho_b = \frac{W_{dry}}{V_{core}} \tag{5}$$

where: ρ_b = soil bulk density (kg/m^3)

$$\rho_{particle} = \frac{W_{wet}}{V_{core}} \tag{6}$$

where: $\rho_{particle}$ = particle density (kg/m^3)

$$\emptyset = 1 - \frac{\rho_b}{\rho_{particle}} \tag{7}$$

where: $\emptyset$ = porosity

The results obtained for the soil moisture content and the soil bulk density for all sample locations are captured in the table below.

Table 4.4: Soil moisture content and soil bulk density.

	Depth of Sample (mm)	**Moist weight x 10^{-3} (kg)**	**Dry Weight x 10^{-3} (kg)**	**%Moisture**	**Porosity ($\emptyset$)**	**BD (kg/m3)**
Soil Sample 12	100-150	280.58	176.43	59.0	0.37	798.3
	300-350	366.32	285.70	28.2	0.22	1292.8
	500-550	417.20	362.64	15.0	0.13	1640.9
Soil Sample 24	100-150	202.94	74.81	171.3	0.63	338.5
	300-350	215.79	81.92	163.4	0.62	370.7
	500-550	217.00	70.60	207.4	0.67	319.5
Soil Sample 15	100-150	379.92	265.77	43.0	0.30	1202.6
	300-350	219.87	100.22	119.4	0.54	453.5
	500-550	207.11	99.83	107.5	0.51	451.7
Soil Sample 9	100-150	309.64	213.01	45.4	0.31	963.8
	300-350	380.78	318.48	19.6	0.16	1441.1
Soil Sample 4	100-150	184.50	104.77	76.1	0.43	474.1
	300-350	428.22	381.45	12.3	0.11	1726.0
	500-550	323.43	278.78	16.0	0.14	1261.4

The bulk densities as calculated and captured in table 4.4 above widely varied which is due to the significantly varied porosities. For example, soil sample 9 porosity is 0.16 at a depth of 300-350mm and for soil sample 24 the porosity is 0.62 at the same depth. It is noted that the sludge land is a large field, i.e. 56.9ha. Since soil porosity is for the most part a physical characteristic of soil, it would not be abnormal for a 56.9ha field to have a non-uniform soil profile.

The information contained in table 4.4 above was used to determine the amount of solute retained for each sample location at various soil depths (see equation (2)). Table 4.5 below shows the calculated distribution coefficient (K_d) and amount of solute retained (S):

Table 4.5: Distribution coefficient and amount of solute retained for soil sample 4.

	Depth of Sample (mm)	**K_d x 10^{-3}(m^3/kg)**	**S (mg/kg)**
Arsenic (As)	100-150	0.76	0.00169
	300-350	0.12	0.000271
	500-550	0.16	0.000355
Cadmium (Cd)	100-150	0.76	0.000761
	300-350	0.12	0.00012
	500-550	0.16	0.00016
Chromium (Cr)	100-150	0.76	0.34072
	300-350	0.12	0.05490
	500-550	0.16	0.07171
Copper (Cu)	100-150	0.76	0.04027
	300-350	0.12	0.00649
	500-550	0.16	0.00848
Lead (Pb)	100-150	0.76	0.01089
	300-350	0.12	0.00175
	500-550	0.16	0.00229
Mercury (Hg)	100-150	0.76	0.00052
	300-350	0.12	0.00008
	500-550	0.16	0.00011
Nickel (Ni)	100-150	0.76	0.00528
	300-350	0.12	0.00085
	500-550	0.16	0.00111
Zinc (Zn)	100-150	0.76	0.15385
	300-350	0.12	0.02479
	500-550	0.16	0.03238

Limitations and assumptions

The historic data that was made available for the purpose of this research was not complete, and this resulted in the need to make assumptions in order to successfully complete the research. In terms of the characteristics (e.g. concentrations of heavy metals and nutrients) of the raw sewage to be processed at the Darvill WWTW, it was assumed that the characteristics of the raw sewage will remain the same at the increased flows.

In this research the worst-case scenario was modelled for the Darvill sludge land. The worst-case scenario was sludge disposal without any removal by means of instant lawn. It was also assumed that the sludge was disposed at a constant daily flow rate and that it was evenly distributed on the Darvill sludge land with a total area of 56.9ha.

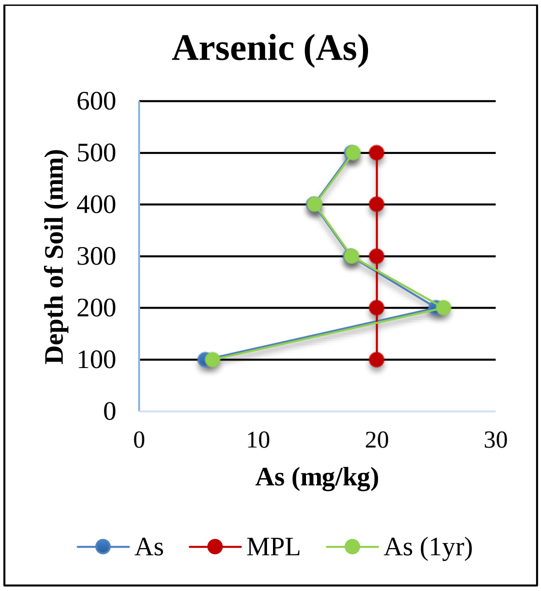
When determining the amount of solute retained in the soil it was assumed that the forward and backward reaction rate coefficient (k_f and k_b respectively) is 1 (h^{-1}) in order to simplify the model. In reality if k_f is more than k_b, the amount of solute retained that would be retained by the soil would be more, if on the other hand k_f is less than k_b the amount of solute retained by the soil would be less.

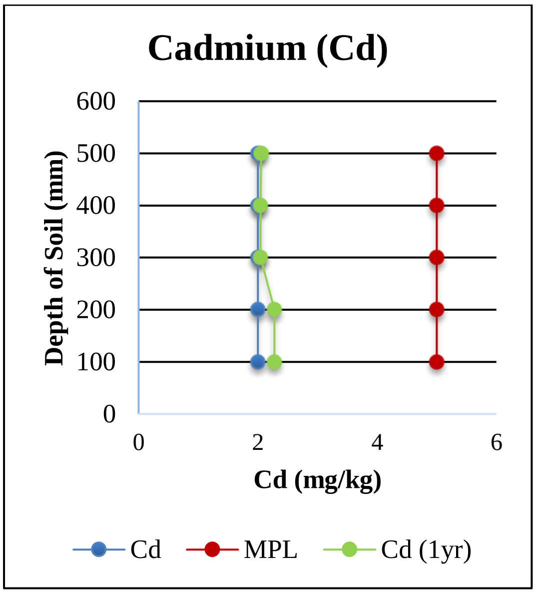
Heavy metal migration in Darvill sludge land

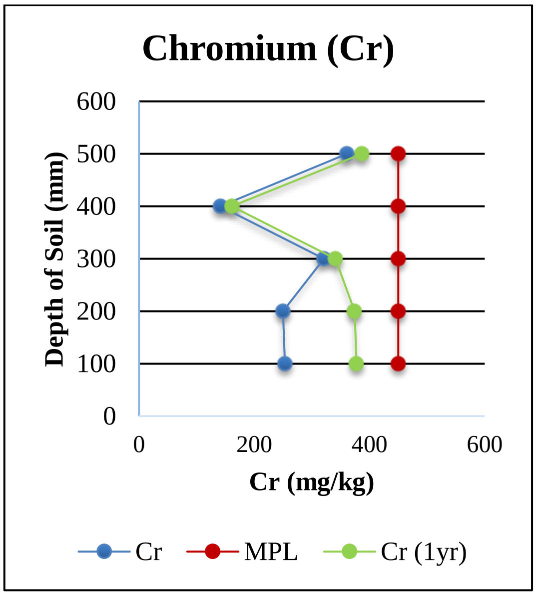
Soil samples were collected from five sample locations at the Darvill sludge land. The soil moisture content and the soil bulk density were determined for each sample location at various depths: 100-150mm, 300-350mm and 500-550mm. Heavy metal concentration present in the Darvill sludge for the year 2013 were obtained from Umgeni Water’s database. Soil bulk density, soil moisture content, and heavy metal concentrations were used to determine the amount of solute retained for all five sample locations at the various depths sampled.

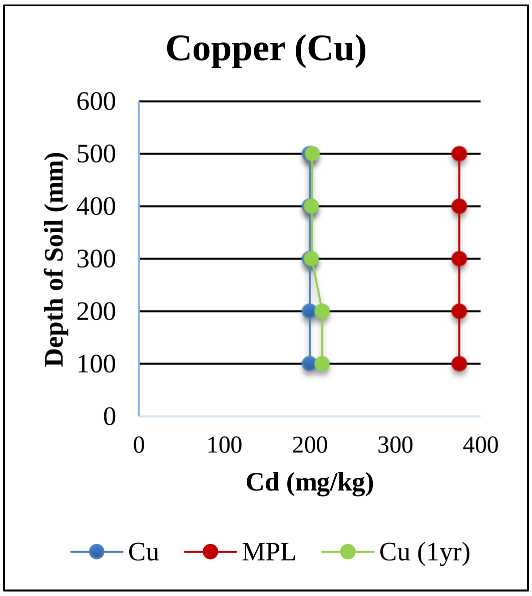
It should be noted that harvesting of the Darvill sludge land grass is done two times over a 12-month cycle and prior to harvesting there is a 30-day holding period. As mentioned above, for the purpose of this model it has been assumed that the disposal of the final effluent is done daily and that it is evenly distributed over the total area of the Darvill sludge land.

The daily amount of solute retained for each sample location at various depths was determined using equation (2) above. The heavy metal concentration present in the soil after a 1-year period of sludge disposal with no removal of grass by means of instant lawn for soil sample 4 is shown in figure 4.29 below. Figure 4.29 illustrates the effects of continuous disposal of sludge at the Darvill sludge land on the amount of heavy metal concentration present in the soil over a period of 1 year. The graphs presented in the figure below illustrates the increase in heavy metal concentration present in the soil due to continuous disposal of sludge over a period of 1 year.









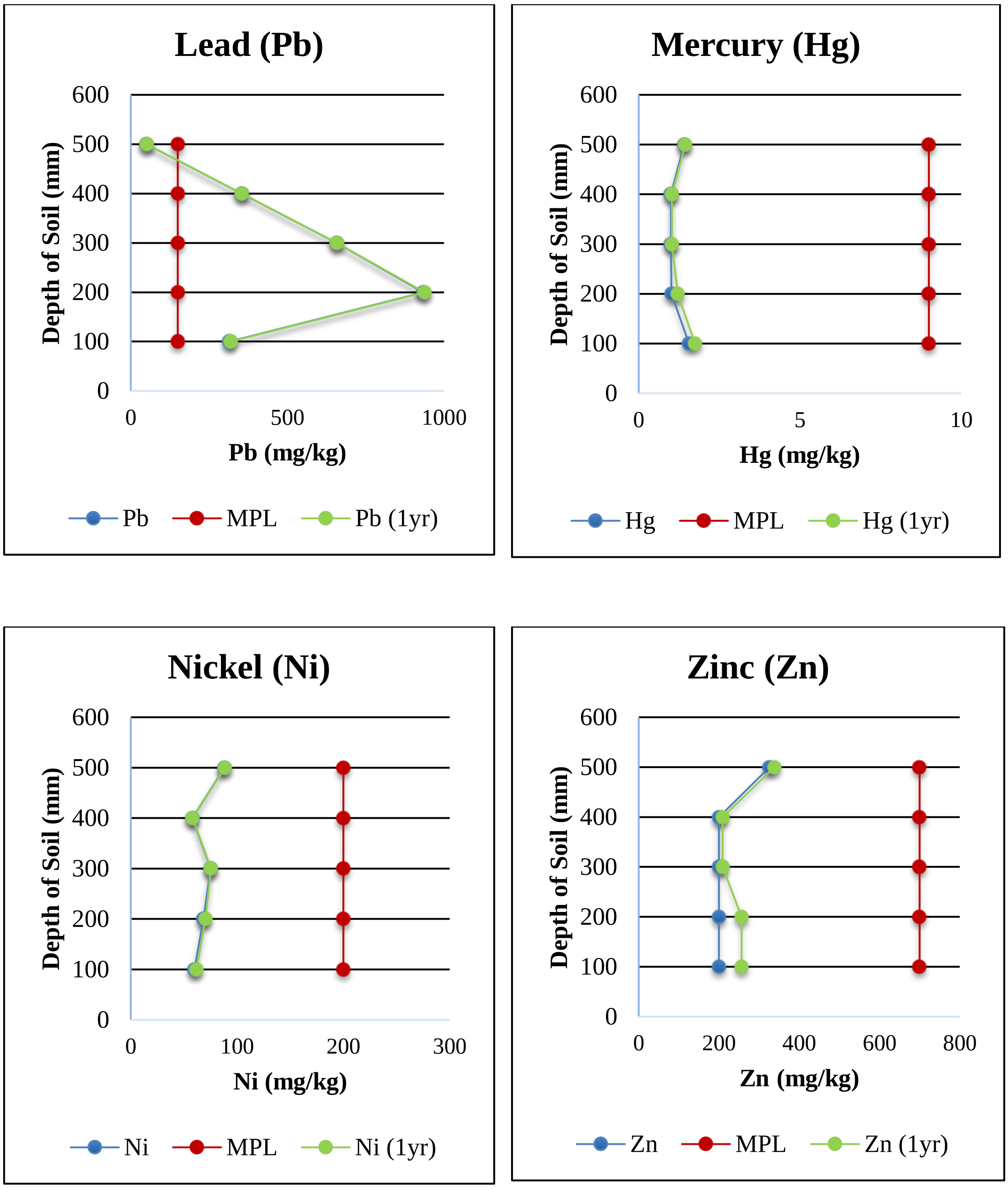
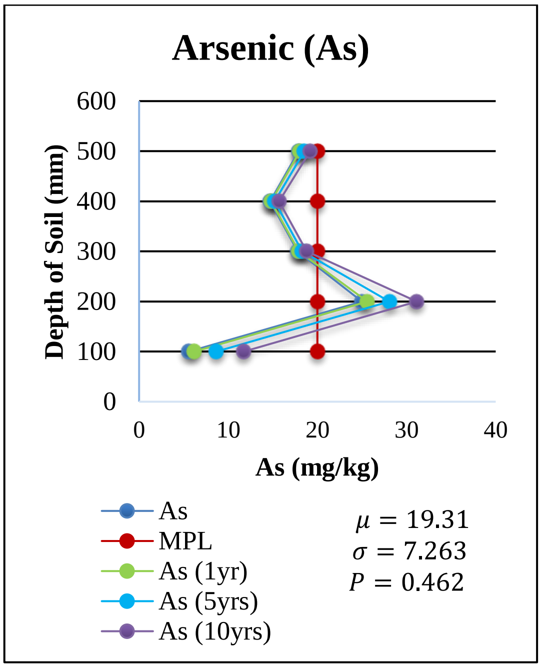
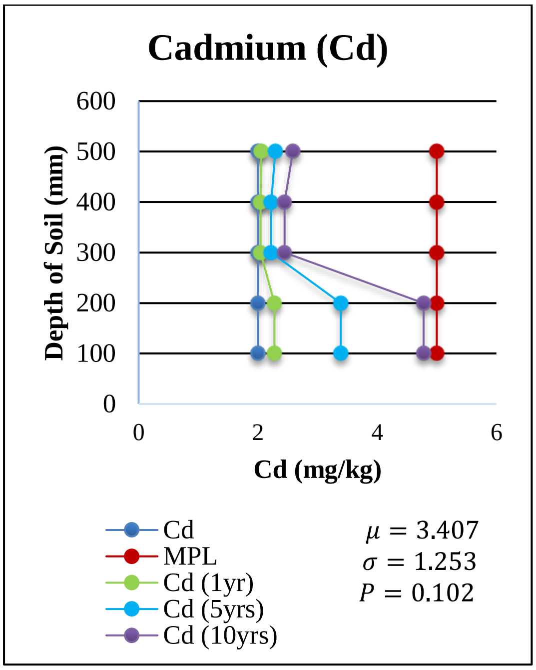


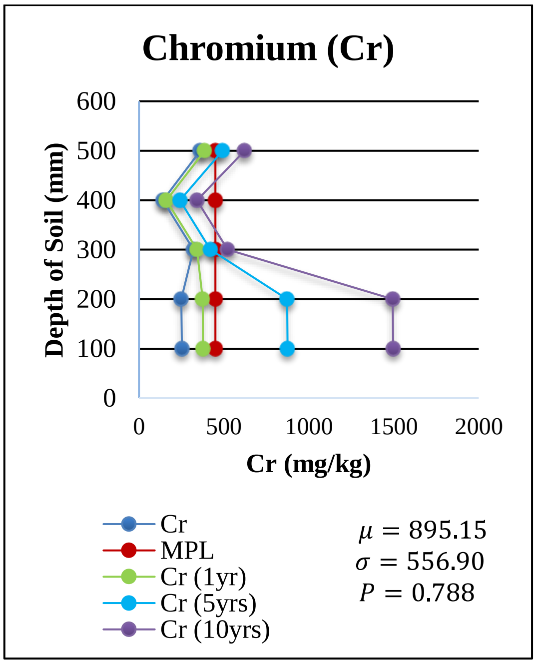
Figure 4.29: Heavy metal concentration for soil sample 4 after 1 year of discharge.

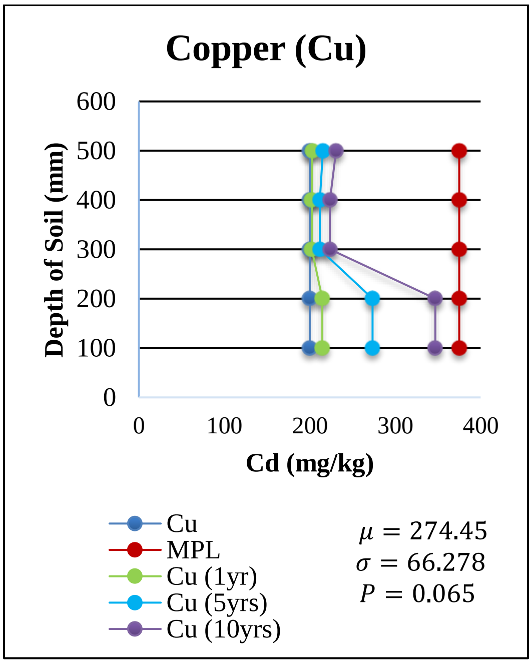
It can be seen on graphs plotted above that there is a significant increase in the concentrations of Cd, Cr, Cu and Zn over time for the top 200mm of soil due to the relatively low soil bulk density and high soil moisture content which resulted in the coefficient of discharge equating to 0.76cm^3/g. It can also be noted that the increase in the heavy metal concentrations present in the soil is relatively low due to the average concentration of the heavy metals present in the sludge discharged onto the Darvill sludge land.

The same exercise was performed for a 5 year period and a 10 year period of sludge discharge with no removal of grass by means of instant lawn. The result of the exercise that was carried out is captured in figure 4.30 below.









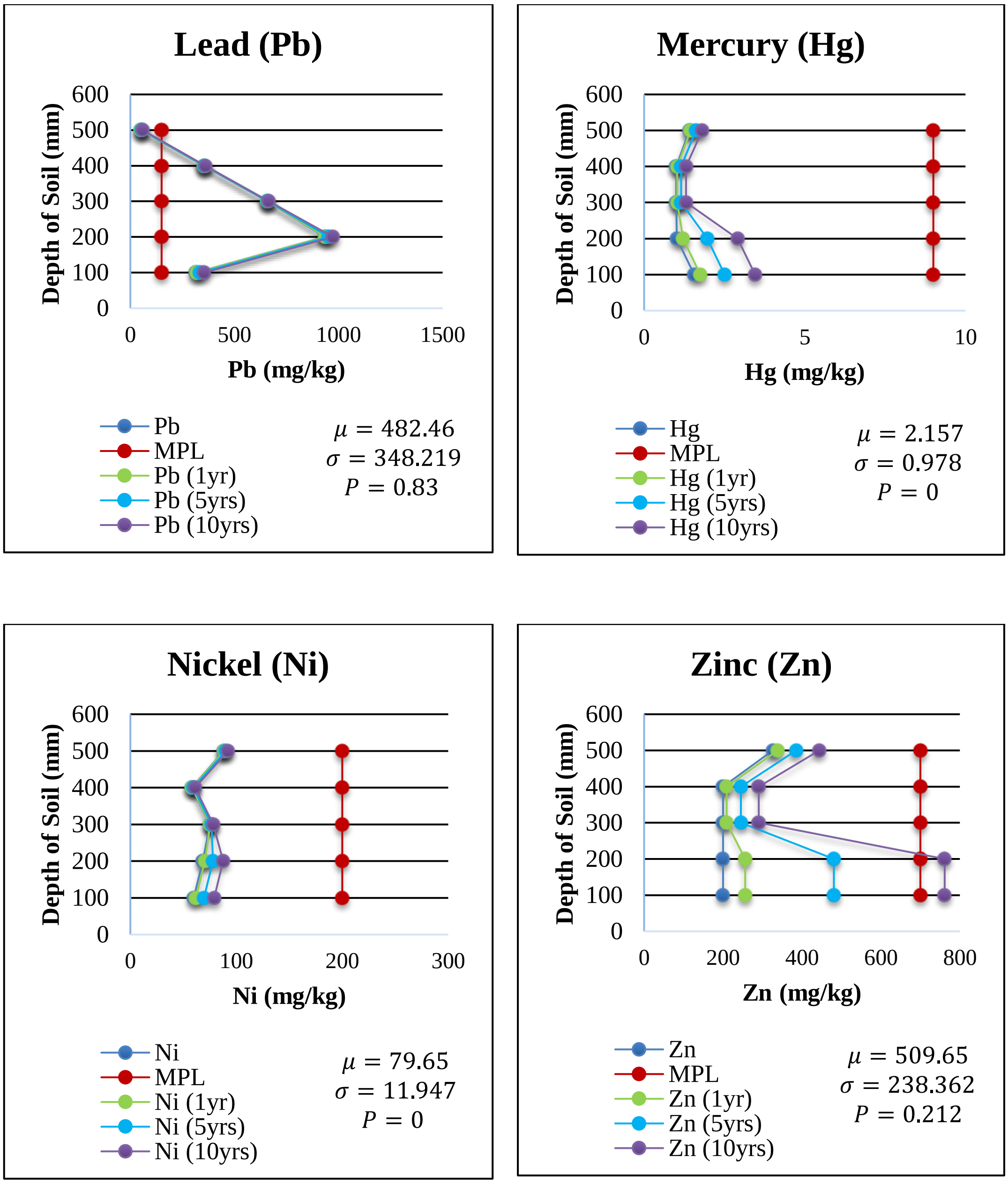


Figure 4.30: Heavy metal concentration for soil sample 4 after 1, 5 and 10 years of discharge.

Based on the graphs plotted above it can be seen that the heavy metal concentrations present in the topsoil generally exceed the maximum permissible level as presented in volume 4 of the Guidelines for Utilisation and Disposal of Wastewater Sludge. In particular, As, Cr, Pb and Zn exceed the MPL when one models the disposal of sludge over a 10 year period with no removal of grass on the Darvill sludge land. The concentrations of Cd and Cu are also of concern when one looks at the projected concentration over a 10 year period. The probability of exceedance of the As, Cr, Pb, and Zn present in the soil after when one models the disposal of sludge over a period of 10 years with no removal of grass is 0.462, 0.788, 0.83 and 0.212, respectively.

As mentioned above, heavy metals of concern are As, Cr, Pb and Zn. The release of high amounts of these heavy metals into the Msunduzi River potentially trigger health and environmental problems. The negative impacts associated with the release of high amounts of Cr include the decrease in plant growth and enzyme activity (Akpor et al., 2014).

Pb is known to be toxic to humans and other living organisms. Pb is particularly dangerous for children. High levels of lead in children can be life threatening and can cause seizures, unconsciousness and death. Pb can be encountered through the consumption of contaminated water. When present in the soil, Pb can be absorbed through plant roots. Ingestion of contaminated plants by animals can pose a risk of lead poisoning. In addition to this, soils with high levels of Pb can pose a risk of lead poisoning especially to children who come into contact with such soils (Tiwari et al., 2013).

Ingestion of small amounts of Zn is essential for survival due to its nature as an essential trace element. However, ingestion of toxic amounts of Zn can be harmful to living organisms. Some of the symptoms of ingestion of toxic amounts of Zn include abdominal pain, nausea and vomiting. In addition to this, effects of ingestion of toxic amounts of Zn include lethargy, anemia and dizziness (Haase et al., 2010).

Ingestion of high amounts of As can have a detrimental effect on the health of living organisms. Drinking water that contains high amounts of As causes characteristic skin manifestation, vascular disease, renal disease, neurological effects, cardiovascular disease, chronic lung disease, cerebrovascular disease, reproductive effects and cancers of skin, kidney and bladder (Kumar et al., 2007).

Darvill sludge land status

For each sample location the average concentration of each element was compared to the MPL and if the average concentration of the element was greater than the MPL it was recommended not to continue with disposal and if the average concentration of the element was less than the MPL it was recommended to continue with disposal. The results were summarised in a form of a table and the results for soil sample 4 can be obtained from table 4.3 above.

For elements with concentrations less than the MPLs, the PAR was determined. In order to be able to determine the PAR for each element the concentration of heavy metals present in the sludge (mg/kg and mg/l) was required. The average heavy metal concentration present in both post thickener 1 and post thickener 2 was used in calculating the PAR. The PAR decreased with the increase in heavy metal concentration present in the sludge.

Having been able to determine the current state of the Darvill sludge land, it was then necessary to take this one step further by predicting the anticipated future concentration of heavy metals present in the sludge land. In order to determine the amount of solute retained by soil, the soil moisture content and soil bulk density needed to be determined. Soil samples were taken from the Darvill sludge land the soil moisture content and soil bulk density were measured at Umgeni Water's laboratory and used to calculate the distribution coefficient (K_d) for the soil at various depths. The distribution coefficient was subsequently used to determine the amount of solute retained for each element at various soil depths, see table 4.5 above.

The same exercise as mentioned above to determine the concentration of heavy metals after a year of disposal with no sludge removal by means of instant lawn was repeated for the 5 year and 10 year model and the results of this exercise have been graphically summarised in figure 4.30 above.

Table 4.6 below summarises the findings of the research report in terms of the projected heavy metal concentration present in the soil against the MPL.

Table 4.6: Summary of projected heavy metal concentration.

	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn	% compliance
Soil sample 4	Year 1								
	✓	✓	✓	✓	X	✓	✓	✓	87.5%
	Year 5								
	X	✓	X	✓	X	✓	✓	✓	62.5%
	Year 10								
	X	✓	X	✓	X	✓	✓	X	50%

	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn	% Compliance
Soil sample 9	Year 1								
	✓	✓	X	✓	X	✓	X	X	50%
	Year 5								
	✓	✓	X	✓	X	✓	X	X	50%
	Year 10								
	✓	✓	X	✓	X	✓	X	X	50%
Soil sample 12	Year 1								
	✓	✓	X	✓	X	✓	X	X	50%
	Year 5								
	✓	✓	X	✓	X	✓	X	X	50%
	Year 10								
	✓	X	X	✓	X	✓	X	X	37.5%
Soil sample 15	Year 1								
	✓	X	X	X	X	X	✓	X	25%
	Year 5								
	✓	X	X	X	X	X	✓	X	25%
	Year 10								
	✓	X	X	X	X	X	✓	X	25%
	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn	% compliance
Soil sample 24	Year 1								
	✓	✓	X	✓	X	✓	✓	X	62.5%
	Year 5								
	✓	X	X	X	X	✓	✓	X	37.5%
	Year 10								
	X	X	X	X	X	X	✓	X	12.5%

X: Does not comply with the Guidelines for the Utilisation and Disposal of Wastewater sludge

✓:Complies with the Guidelines for the Utilisation and Disposal of Wastewater sludge

Ground water monitoring

The Darvill WWTW has a total of seven monitoring boreholes and one reference borehole, see table 4.7 below. Figure 4.31 to 4.38 below is a graphic representation of the concentration of nitrate (NO_3) present in the groundwater samples versus the maximum acceptable concentration of nitrate present in groundwater intended to be used for drinking purposes (10mg/l) as mentioned in the South African Water Quality Guidelines.

Table 4.7: Nitrate concentration present in the groundwater samples.

Description	**Borehole depth (m)**	**Max. Acceptable Level (mg/l)**
Darvill borehole A1	40	10
Darvill borehole B0 (reference borehole)	25	
Darvill borehole B4	15	
Darvill borehole C1	3.5	
Darvill borehole C2	4.5	
Darvill borehole C3	25	
Darvill borehole C4	3.0	
Darvill borehole F1	21.3	

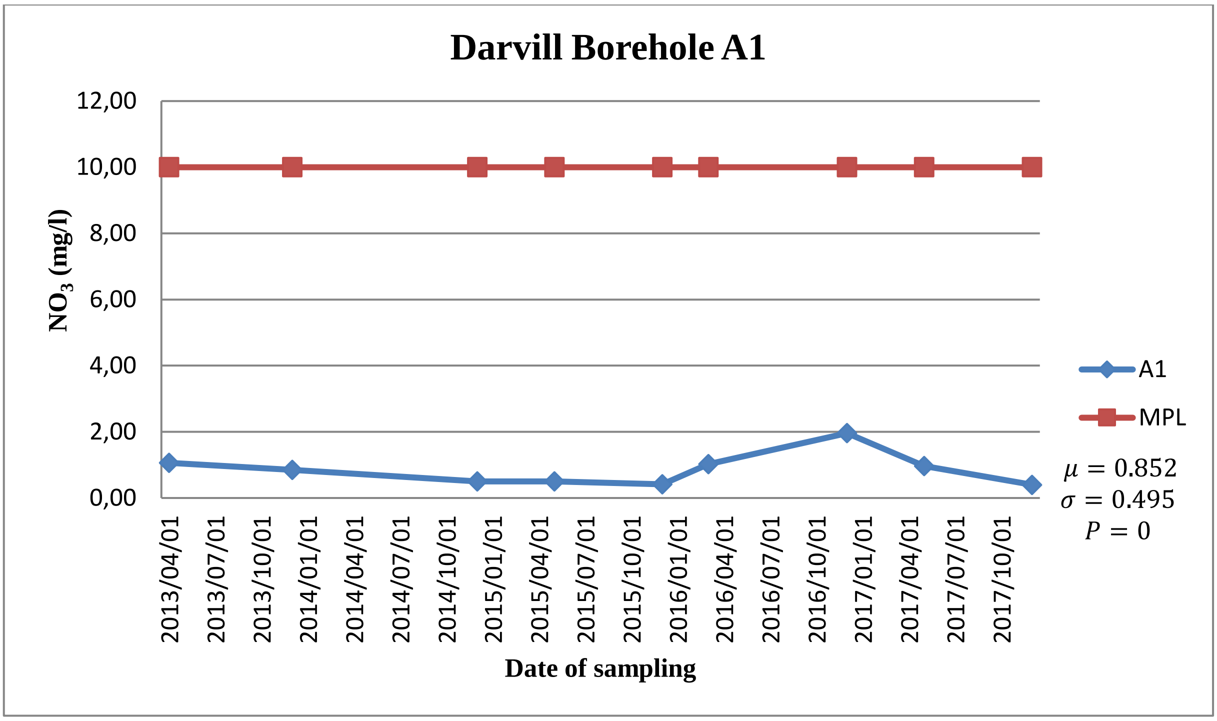


Figure 4.31: Concentration of NO_3 measured at the Darvill Borehole A1.

The Concentration of NO_3 was measured twice a year at the Darvill monitoring borehole then plotted in figure 4.31. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole A1 stayed below the maximum acceptable concentration of NO_3. The maximum measured concentration of NO_3 was 1.96mg/l, the minimum measured concentration was 0.40mg/l, and an average concentration of 0.85mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.31 above was determined and presented in figure 4.31. The probability of exceedance of the concentration of NO_3 is 0.

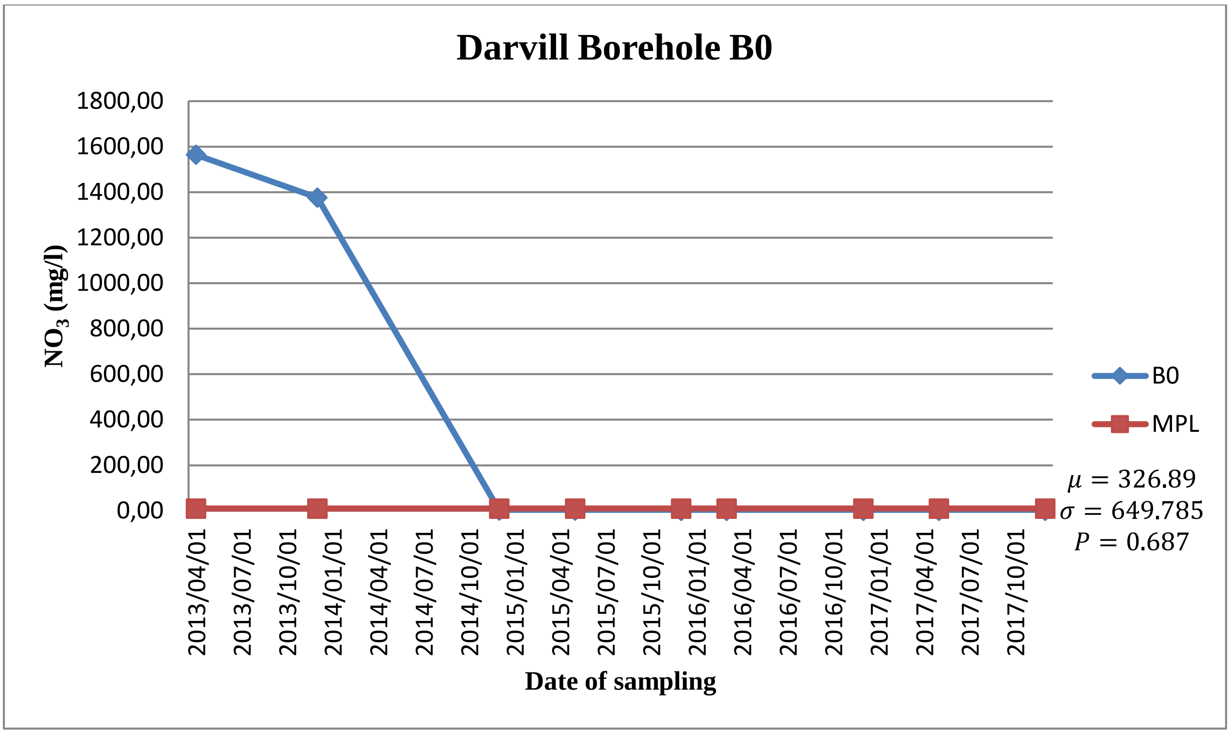


Figure 4.32: Concentration of NO_3 measured at Darvill borehole B0.

The concentration of NO_3 was measured twice a year at the Darvill monitoring borehole then plotted in figure 4.32. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole B0 exceeded the maximum allowable concentration during the month of April 2013 and April 2014. The maximum measured concentration of NO_3 was 1 564mg/l, the minimum measured concentration was 0.10mg/l, and an average concentration of 326.86mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.32 above was determined and presented in figure 4.32. The probability of exceedance of the concentration of NO_3 is 0.687.

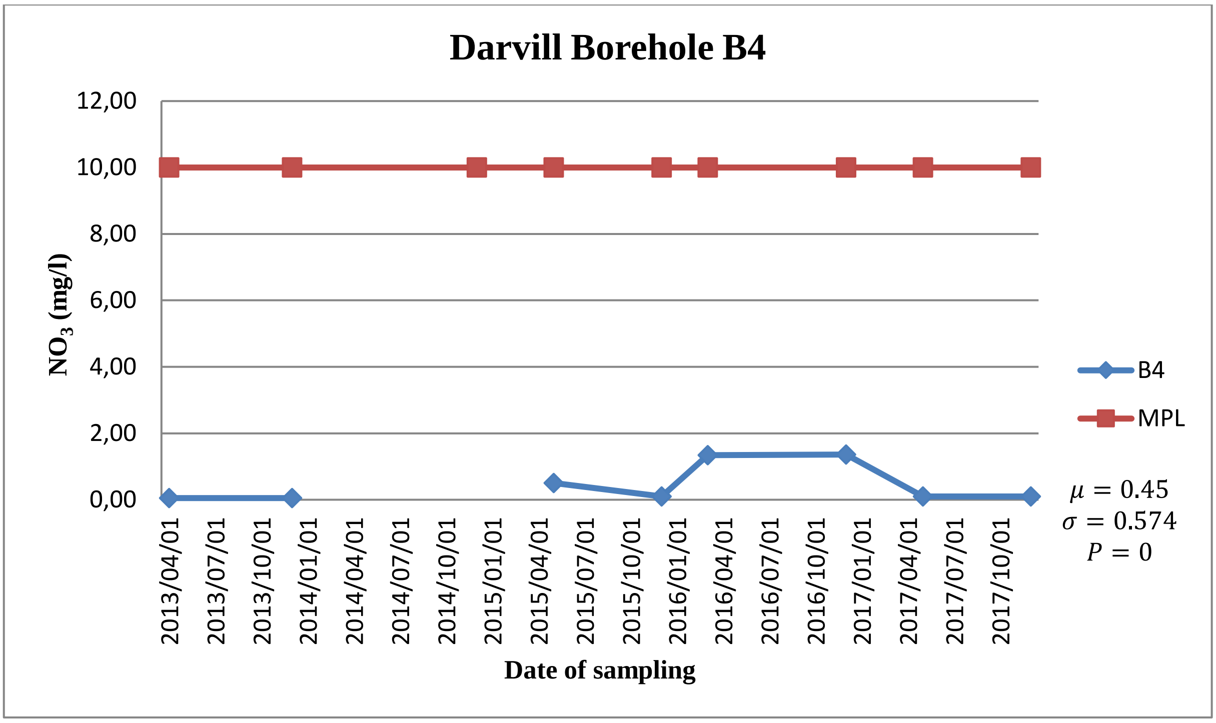


Figure 4.33: Concentration of NO_3 measured at Darvill borehole B4.

The concentration of NO_3 was measured twice a year at the Darvill monitoring borehole from 2013 to 2017, with the exception of the year 2014, and then plotted in figure 4.33. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole B4 stayed below the maximum allowable concentration. The maximum measured concentration of NO_3 was 1.36mg/l, the minimum measured concentration was 0.05mg/l, and an average concentration of 0.45mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.33 above was determined and presented in figure 4.33. The probability of exceedance of the concentration of NO_3 is 0.

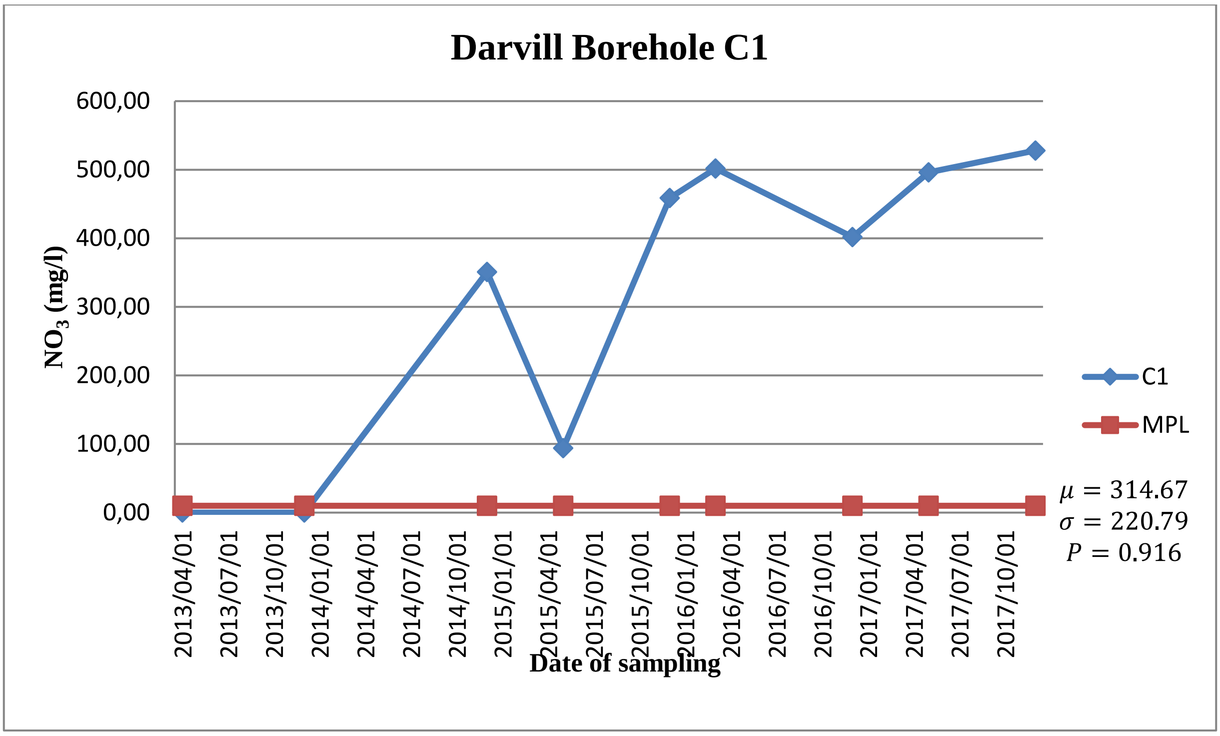


Figure 4.34: Concentration of NO_3 measured at Darvill borehole C1.

The concentration of NO_3 was measured twice a year at the Darvill monitoring borehole then plotted in figure 4.34. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole C1 exceeded the maximum allowable concentration during the year 2014, 2015, 2016 and 2017. The maximum measured concentration of NO_3 was 528mg/l, the minimum measured concentration was 0.05mg/l, and an average concentration of 314.67mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.34 above was determined and presented in figure 4.34. The probability of exceedance of the concentration of NO_3 is 0.916.

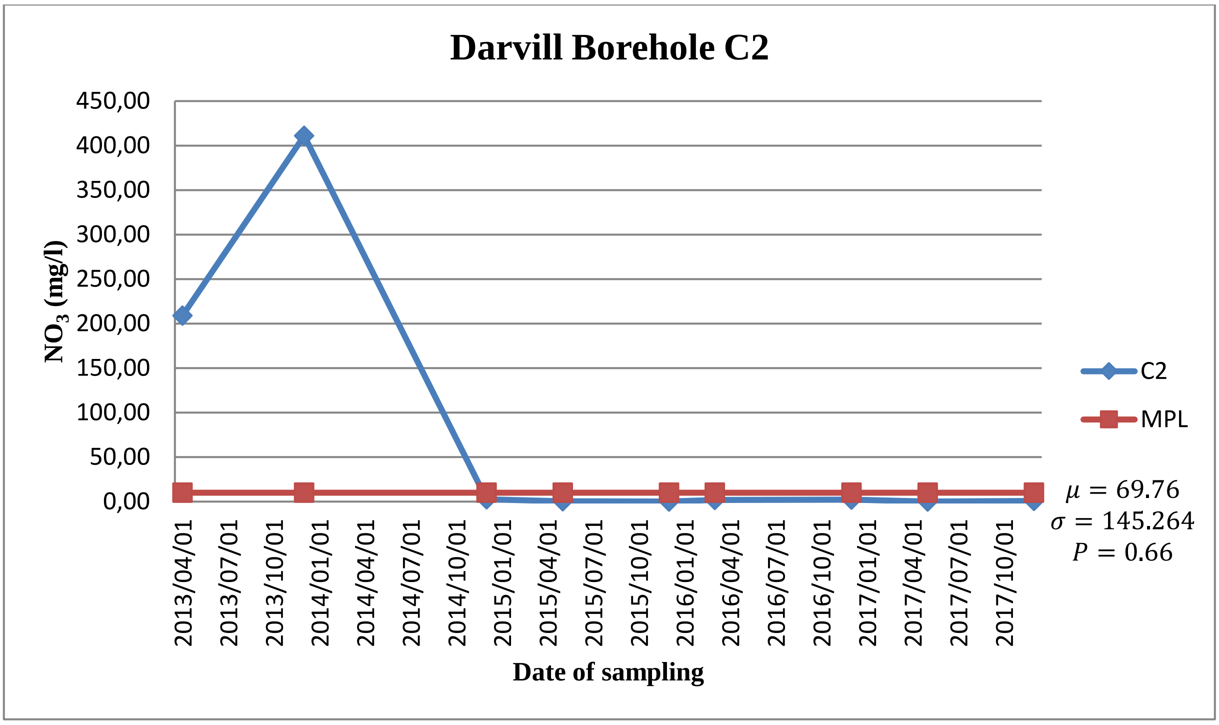


Figure 4.35: Concentration of NO_3 measured at Darvill borehole C2.

The concentration of NO_3 was measured twice a year at the Darvill monitoring borehole then plotted in figure 4.35. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole C2 exceeded the maximum allowable concentration during the month of April and December 2013. The maximum measured concentration of NO_3 was 411mg/l, the minimum measured concentration was 0.1mg/l, and an average concentration of 69.77mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.35 above was determined and presented in figure 4.35. The probability of exceedance of the concentration of NO_3 is 0.66.

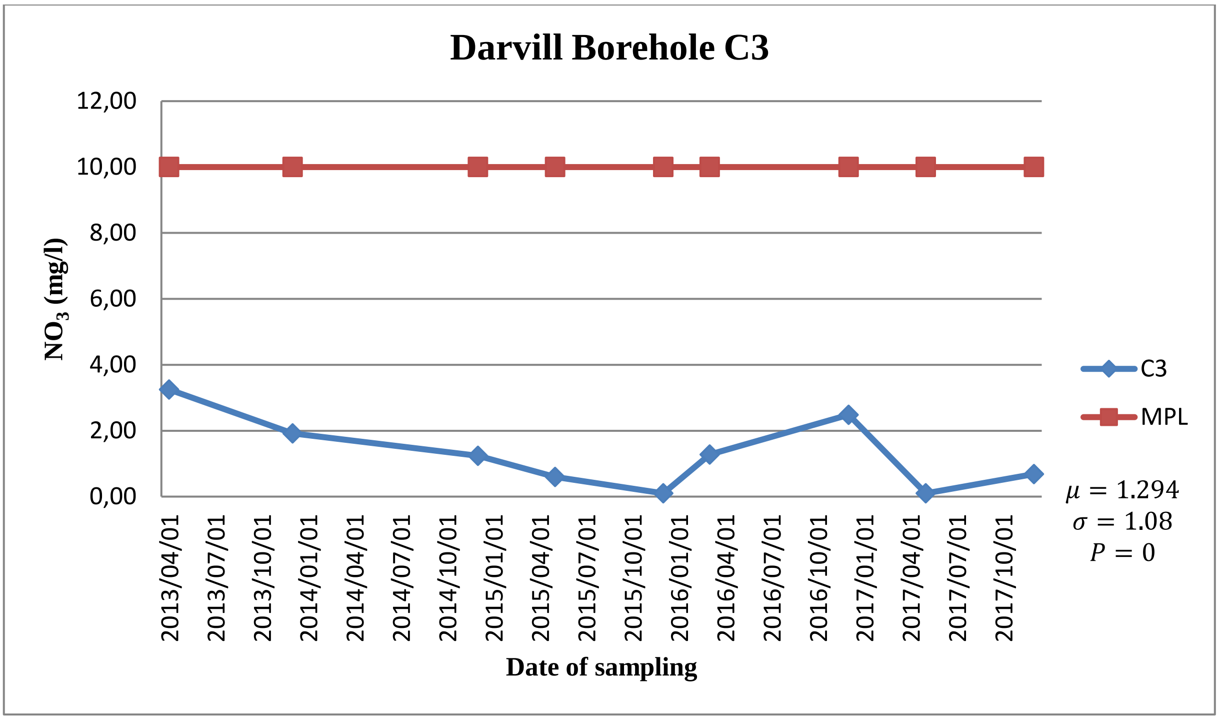


Figure 4.36: Concentration of NO_3 measured at Darvill borehole C3.

The concentration of NO_3 was measured twice a year at the Darvill monitoring borehole then plotted in figure 4.36. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole C_3 stayed below the maximum allowable concentration. The maximum measured concentration of NO_3 was 3.25mg/l, the minimum measured concentration was 0.10mg/l, and an average concentration of 1.29mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.36 above was determined and presented in figure 4.36. The probability of exceedance of the concentration of NO_3 is 0.

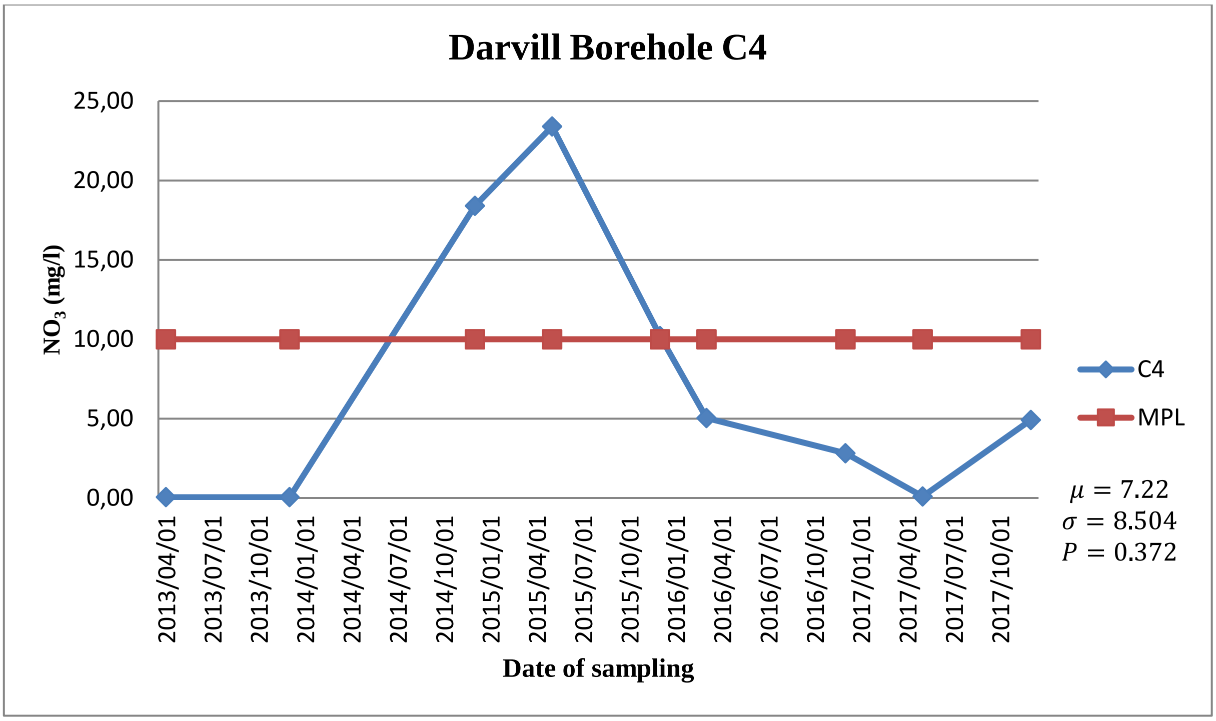


Figure 4.37: Concentration of NO_3 measured at Darvill borehole C4.

The concentration of NO_3 was measured twice a year at the Darvill monitoring borehole then plotted in figure 4.37. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole C4 exceeded the maximum acceptable concentration during the month of December 2014 and May 2015. The maximum measured concentration of NO_3 was 23.4mg/l, the minimum measured concentration was 0.10mg/l, and an average concentration of 7.22mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.37 above was determined and presented in figure 4.37. The probability of exceedance of the concentration of NO_3 is 0.372.

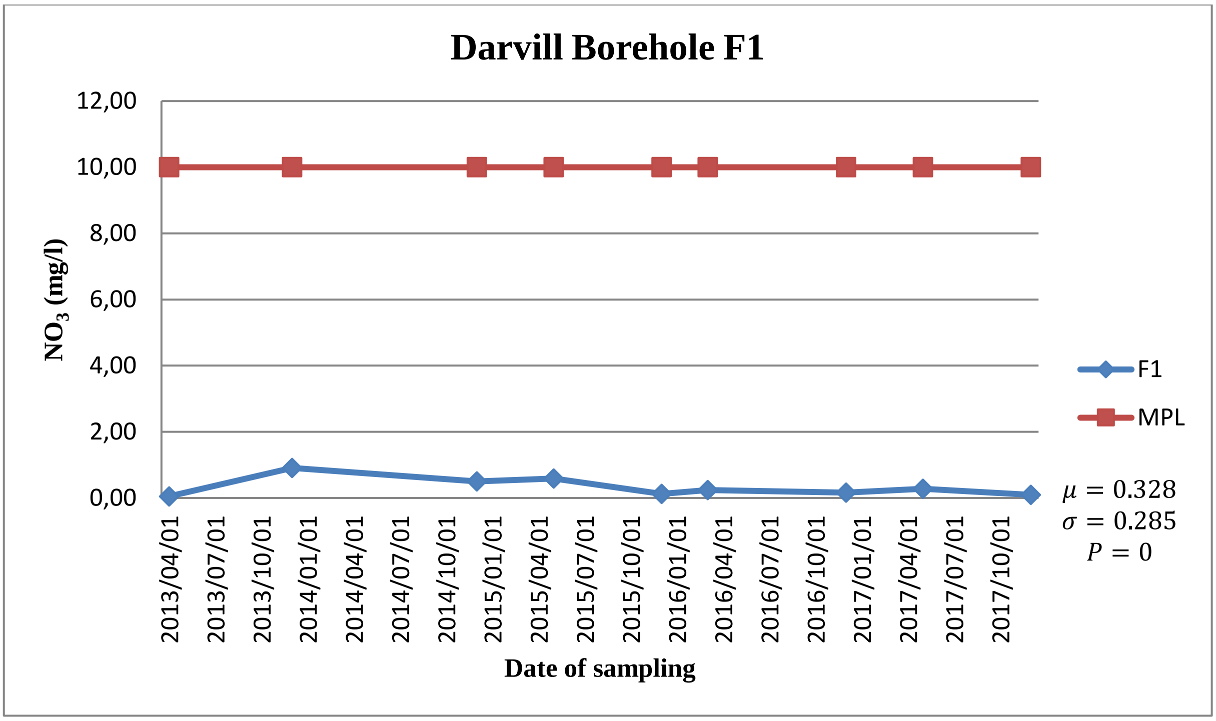


Figure 4.38: Concentration of NO_3 measured at Darvill borehole F1.

The concentration of NO_3 was measured twice a year at the Darvill monitoring borehole then plotted in figure 4.38. As can be seen from the graph above, the concentration of NO_3 measured at the Darvill borehole F1 stayed below the maximum allowable concentration. The maximum measured concentration of NO_3 was 0.91mg/l, the minimum measured concentration was 0.10mg/l, and an average concentration of 0.33mg/l. The mean (μ), standard deviation (σ) and probability of exceedance (P) for the dataset presented in the figure 4.38 above was determined and presented in figure 4.38. The probability of exceedance of the concentration of NO_3 is 0.

Based on the information in figures 4.31 to 4.38 it can be seen that monitoring borehole B0, C1 and C2 is of concern as the concentration of NO_3 measured from 2013 to 2017 exceeded the maximum allowable concentration on a number of occasions. The concentration of NO_3 measured at the Darvill borehole B0 exceeded the maximum allowable concentration during the month of April 2013 and April 2014. The probability of exceedance of the maximum allowable concentration of NO_3 is 0.687. It is also noted that the measured concentration of NO_3 from May 2014 to October 2017 stayed below the maximum allowable concentration.

The concentration of NO_3 measured at the Darvill borehole C1 exceeded the maximum allowable concentration during the year 2014, 2015, 2016 and 2017. Further to this, the probability of exceedance of the MPL of NO_3 is 0.916. Monitoring borehole C1 is located in close proximity to the maturation river which contains chlorinated effluent. The high NO_3 concentration present in monitoring borehole C1 may be due to human activities such as agriculture and stormwater runoff which affects the quality of the wastewater as well as continuous discharge of sludge containing NO_3.

The concentration of NO_3 measured at the Darvill borehole C2 exceeded the maximum allowable concentration during the month of April and December 2013. The probability of exceedance of the maximum allowable concentration of NO_3 is 0.66. It is also noted that the measured concentration of NO_3 from January 2014 to October 2017 stayed below the maximum allowable concentration.

The presence of high amounts of NO_3 in groundwater is of concern as this can cause environmental and health problems. Excessive amounts of nutrients in water bodies can trigger eutrophication. This can result in the formation of algal blooms which causes the depletion of oxygen in the water body, blocking of sunlight penetration into the water column and the potential production of toxins. The depletion of oxygen in a water body can trigger fish kills. In addition to this the consumption of water with excessive amounts of NO_3 can cause health problems such as methemoglobinemia, cancer, adverse reproductive outcomes, diabetes and thyroid conditions to humans (Stubbs, 2016).

General observations

The Darvill WWTW is located on the western outskirts of Pietermaritzburg and the majority of the site slopes gently at about 1.5 to 3 degrees dipping in a north easterly direction (Bester & Hughes, 2014). The Darvill sludge land slopes from the top of the site (southwest) down to the Msunduzi River (northeast).

The Darvill sludge land has a total of 8 boreholes which includes 1 reference borehole. As mentioned above monitoring borehole C1 is of concern as the concentration of NO_3 measured from 2013 to 2017 was above the maximum allowable concentration.

In addition to the above mentioned, for the purpose of this research, a total of 5 soil sample locations were sampled and analysed and from these samples it is noticed that the concentration of Pb, Cr and Zn exceeded the MPLs. For all 5 soil sample locations the amount of solute retained is higher in the top 200mm of soil and then decreases with increasing soil depth. This is as a result of the sludge application rate over time as well as the quality of sludge disposed at the sludge land. The soil data for 2013 shows that the concentration of As, Cr, Pb and Zn exceeds the MPLs which is concerning.

4.3 Discussion

Rainfall

The Darvill WWTW is responsible for the treatment of wastewater generated in Pietermaritzburg, KwaZulu-Natal. The Darvill WWTW experiences an increase in volumes of sewage entering the WWTW during rainy seasons as a result of stormwater runoff entering the sewer lines due to poor reticulation system in the city. This results in the overloading of the WWTW which has an effect on the performance of the WWTW. The rainfall data shown in table 4.1 ranges between 69 and 101mm. From the table, it can be seen that the highest average rainfall recorded over a period of 12 months was during the summer months and the lowest average rainfall recorded over a period of 12 months was during the winter months, as expected. The concentration of As, Cd, Cu, Pb, Hg, Ni and Zn present in post thickener 1 and post thickener 2 recorded in figure 4.1 – 4.8 is highest during the summer months (January and February).

Based on previous research (Yan et al., 2012; Lacy, 2009; Muthukrishnan, 2010), wear of automobiles and road surfaces results in the deposition of heavy metals such as Cu, Zn, Pb, Ni and Cd on roadsides. During rainfall events the heavy metals present on roadsides enter the sewer lines due to poor reticultation system and are transported to WWTWs. The sources of heavy metals present on roadsides include fuel combustion, lubricating oil consumption and tyre wear (Yan et al., 2012). Lubricating oil consumption and tyre wear result in the emission of Cd. Brake wear is the main source of Cu and Pb emission, and Zn comes from galvanized parts such as fuel tanks (Yan et al., 2012).

It is also noted that the concentration of heavy metals present in post thickener 1 is higher than that of post thickener 2. This is due to the fact that sludge contained in the post thickeners come from different sources. The activated sludge from the reactor basin is taken into the DAF tank where removal of suspended solids takes place. The solids from the DAF tank are taken to post thickener 2. The solids from the anaerobic digesters are taken to post thickener 1.

Heavy metal present in soils

The Guidelines for Utilisation and Disposal of Wastewater (Volume 4) were developed to enable beneficial use of sludge without harming the environment. Limits have been set for heavy metals present in the soil in order to ensure that the soil quality does not degrade to a point where remediation would be necessary.

Arsenic (As):

The concentration of As present in the receiving soil should stay below 20mg/kg as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). Figure 4.20 shows that the concentration of As for all five soil samples was below the MPL. This result is acceptable for the receiving soil. However, when compared to figure 4.30 above, it can be seen that the projected concentration of As at 200mm depth exceeds the MPL and is approaching the MPL at 500mm depth.

A possible cause of stability of As across all five soil samples is the low levels of metals present in the incoming wastewater and the low levels of stormwater runoff. The low levels of As present in soil could be due to the low rainfall during the time of sampling, which was in August 2013 which had an average rainfall of 70mm. This result was expected since during periods of low rainfall, the stormwater runoff which contains traces of heavy metals is low.

Cadmium (Cd):

The concentration of Cd present in the receiving soil should stay below 5mg/kg as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). Figure 4.21 shows that the concentration of Cd for all five soil samples was below the MPL. This result is acceptable for the receiving soil. The concentration of Cd measured is below the MPL which ensures the protection of soil against the degradation of the soil quality to an extent that remediation would be necessary. However, when compared to figure 4.30 above, it can be seen that the projected concentration of Cd after 10 years of sludge disposal is approaching the MPL which will result in the need for remediation.

Chromium (Cr):

The concentration of Cr present in the receiving soils is regulated by the Guidelines for Utilisation and Disposal of Wastewater (Volume 4). The MPL of Cr present in the receiving soil is 450mg/kg as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4). Figure 4.22 shows that the concentration of Cr measured ranges between 265.2 and 1 717.2mg/kg. This result is unacceptable for the receiving soil as the measured concentration of Cr for two out of the five soil samples exceed the MPL. A possible cause of the excessive concentration of Cr present in the receiving soil is the discharge of industrial waste, namely, metallurgical and chemical industries which are important industrial sources of Cr (EPA, 1998; ATSDR, 2000), and stormwater runoff containing traces of Cr. Plants require certain amounts of heavy metals in order to ensure their growth, but excessive amounts of heavy metals can degrade the soil quality. In addition to this excessive amounts of heavy metals can result in the contamination of groundwater through leaching of these heavy metals (Chibuike & Obiora, 2014).

To ensure compliance with the Guidelines for Utilisation and Disposal of Wastewater, the concentration of Cr present in the receiving soil requires reduction. Westgate (2014) mentioned that the removal of 200mm of soil from the Darvill sludge land and the application of lime and returning the 200mm top soil layer can be used to stabilise Cr to a less soluble form. While this is true, this still retains potential to cause issue because changes in the soil chemistry can result in the remobilisation of Cr. Furthermore, soil samples taken from site 12 and 24 already contain Cr above the MPL meaning that the discharge of sludge containing Cr is not desirable. above mentioned means that discharge of sludge at sample site 12 and sample site 24 is not recommended as the concentration of Cr measured at these sample sites exceed the MPL.

In addition to the above mentioned it is important to reduce the concentration of heavy metals present in the industrial waste by means of pre-treatment at the source and imposing discharge limits and ensuring continuous monitoring in order to comply with the set discharge limits.

Copper (Cu):

The concentration of Cu present in the receiving soil is regulated by the Guidelines for Utilisation and Disposal of Wastewater (Volume 4). The MPL of Cu is 375mg/kg as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). Figure 4.23 shows that the concentration of Cu measured was below the MPL and ranges between 200 and 295.8 mg/kg. This result is acceptable as it illustrates that the current concentration of Cu present in the soil stayed below the MPL. However, when compared to figure 4.30 above, it can be seen that the projected concentration of Cu after 10 years of sludge disposal is approaching the MPL which will result in the need for remediation. Therefore it is continuously monitor the concentration of Cu present in the soil in order to ensure that the soil quality does not degrade to an extent that remediation would be necessary.

Lead (Pb):

The concentration of Pb present in the receiving soil is regulated by the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The MPL for Pb is 150mg/kg as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4). Figure 4.24 shows that the concentration of Pb at the Darvill sludge land ranges between 99.9 and 462.3mg/kg with three out of the five soil samples exceeding the MPL. This result is unacceptable. A possible cause of the excessive levels of Pb in the soil is the stormwater runoff which contains traces of heavy metals, including Pb from brake wear and paint used for road markings (Lacy, 2009). When sludge containing Pb is discharged onto the sludge lands, some of the solute is retained in the soil, and the remaining amount if not retained by the soil will migrate or decay.

Pb is a well-known toxic metal which is considered as a priority pollutant (Arbabi et al., 2015). Pb generally enters the ecosystem through soil, air and water. Pb may enter water resources through direct discharge from industries and it may also contaminate groundwater through leaching of this heavy metal (Arbabi et al., 2015; Chibuike & Obiora, 2014). Pb is known to cause anaemia, kidney malfunction and brain tissue damage (Arbabi et al., 2015).

As previously mentioned, the concentration of Pb measured at sample site 4, 15 and 24 is unacceptable as it exceeds the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). To ensure that the concentration of Pb in the soil does not continue to increase uncontrollably, treatment of industrial wastewater is required to take place prior to discharging into sewage systems. There are various methods that are currently used for Pb removal from industrial wastewater which includes chemical precipitation, electrochemical reduction, ion exchange, reverse osmosis, membrane separation and adsorption (Arbabi et al., 2015). The depth at which shallow groundwater moves around the sludge land is not known. Deep cut off drains on the downhill side of the Darvill sludge land could be provided in order to intercept subsurface soil water flows which could potentially contain traces of heavy metals (Westgate, 2014).

Pb is known to be toxic to humans and other living organisms. Pb is particularly dangerous for children. High levels of lead in children can be life threatening and can cause seizures, unconsciousness and death. Pb can be encountered through the consumption of contaminated water. When present in the soil, Pb can be absorbed through plant roots. Ingestion of contaminated plants by animals can pose a risk of lead poisoning. In addition to this, soils with high levels of Pb can pose a risk of lead poisoning especially to children who come into contact with such soils (Tiwari et al., 2013).

Mercury (Hg):

The concentration of Hg present in the receiving soil is regulated by the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The MPL of Hg is 9mg/kg as set out in the guidelines. Figure 4.25 shows that the concentration of Hg measured for all five soil samples stayed below the MPL. The concentration of Hg measured ranges between 1.2 and 4.0mg/kg. This result is acceptable for the receiving soil. Continuous monitoring of the concentration of Hg present in the soil is required to ensure compliance with the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006).

Nickel (Ni):

The concentration of Ni present in the receiving soil is regulated by the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The MPL of Ni is 200mg/kg as set out in the guidelines. Figure 4.26 shows that that the concentration of Ni measured for all five sample sites stayed below the MPL and the concentration ranges between 18 and 147.4mg/kg. This result is acceptable for the receiving soil. Continuous monitoring of the concentration of Ni present in the soil is required to ensure compliance with the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006).

Zinc (Zn):

The concentration of Zn present in the receiving soil is regulated by the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) (2006). The MPL of Zn is 700mg/kg as set out in the guidelines. Figure 4.27 shows that the concentration of Zn measured ranges between 225.2 and 1 338.2mg/kg. This result is unacceptable as the measured concentration of Zn for two out of the five soil samples exceed the MPL. A possible cause of the excessive levels of Zn present in the soil is the stormwater runoff which contains traces of heavy metals, including Zn from galvanised parts such as fuel tanks (Yan et al., 2012). Excessive levels of Zn is generally not as toxic as other heavy metals, however it has shown to be toxic when it enters the ecosystem, namely, saltwater animals are known to be sensitive to high levels of Zn. (Yan et al., 2012). In order to protect water resources deep cut off drains on the downhill side of the Darvill sludge land could be provided in order to intercept subsurface soil water flows which could potentially contain traces of heavy metals (Westgate, 2014). The depth at which the shallow groundwater moves around the sludge land is unknown. Deep cut of drains on the downhill side of the Darvill sludge land could be provided in order to intercept subsurface soil water flows which could potentially contain traces of heavy metals.

Heavy metal migration at the Darvill sludge land

Having established the current levels of metals in the Darvill sludge land, a model to predict future concentrations of heavy metals was created. The model created has soil moisture content and soil bulk density as inputs. The concentration of heavy metals present in the receiving soil is regulated by the Guidelines for Utilisation and Disposal of Wastewater (Volume 4). Table 4.5 shows the amount of solute retained for soil sample 4 at various depths: 100-150mm, 300-350mm and 500-550mm. Figure 4.30 shows the heavy metal concentration for soil sample 4 after 1, 5 and 10 years of discharge sludge at the Darvill sludge land. As can be seen from the graph, the concentration of Cd, Cr, Cu, Hg and Zn is highest in the top 100-150mm of the soil. This result is expected and is supported by research conducted by Herselman et al. (2005) which mentioned that in the short term the mobility of heavy metals in receiving soils was limited to the top 50-100mm of the soil.

Based on the results presented in figure 4.30, the concentration of As, Cr, Pb and Zn after 10 years of sludge discharge at the Darvill sludge land exceeds the MPL as set out in the Guidelines for Utilisation and Disposal of Wastewater (Volume 4). In order to ensure that the concentration of heavy metals present in the Darvill sludge land does not deteriorate further, remedial measures are required. Research conducted by Herselman et al. (2005) mentioned that mobility of heavy metals is enhanced when the pH of soil is low, namely, when pH is below 5. Therefore the application of lime in order to increase the pH of acidic soils can result in the reduction of the mobility of heavy metals. Increased mobility of heavy metals away from a specific piece of land may result in the decrease of the accumulated concentrations of heavy metals except for when the migration out of that specific poiece of land is balanced by an influx of heavy metals to that same piece of land and/or production/decay through reactions taking place in that piece of land. The Removal the top soil to a depth of 200mm can also has potential to reduce the concentration of heavy metals contained in the top soil. In addition to this, deep cut off drains could be provided on the downhill side of the Darvill sludge land to intercept subsurface water flows which could potentially contain traces of heavy metals (Westgate, 2014).

Groundwater monitoring boreholes

The South African Water Quality Guidelines (1996) regulate the concentration of nitrate (NO_3) present in groundwater intended to be used for drinking purposes. The maximum acceptable concentration of NO_3 present in groundwater is 10mg/l. Figures 4.31 to 4.38 above show the concentration of NO_3 measured at the monitoring boreholes from the year 2013 to 2017. As can be seen from these figures, the concentration of NO_3 for one of the seven monitoring boreholes exceeds the maximum acceptable level from the year 2013 to 2017, which indicates leaching of NO_3. To ensure that groundwater contamination as a result of the excessive concentration of NO_3 is not an issue, cut off drains could be provided on the downhill side of the Darvill sludge land to intercept subsurface water flows.

In addition to the abovementioned, the most appropriate method of controlling NO_3 concentrations in groundwater is the prevention of contamination at the source. This can be achieved by applying appropriate methods of managing agricultural practices, the controlling of sewage leakage, and the management of animal manure and fertilizer application and storage (WHO, 2011). The controlling of stormwater ingress into the wastewater collection system can be achieved by the removal of illegal direct connections and the maintenance and rehabilitation of aging wastewater collection systems. In order to ensure sustainability of the aforementioned method of controlling stormwater ingress into the wastewater collection system, continuous monitoring and enforcement is required. These interventions will reduce NO_3 loading into the WWTW. There are also several mechanisms through which the treatment plant can also ensure a lower NO_3 loading to the receiving environment, i.e., physicochemical or biological treatment and sometimes a combination of both (Matrella et al., 2014).

Groundwater remediation for borehole C1 is required in order to reduce the contaminant concentration to acceptable standards. This can be achieved by pumping out the contaminated groundwater and treating it to acceptable standards prior to discharging into the receiving environment. The treatment of the contaminated groundwater can be achieved by way of biological or chemical means. Biological treatment involves the use of organic matter, microorganisms and plants to clean the contaminated water. Chemical treatment involves the use of chemicals to clean the contaminated water to acceptable standards. These include carbon absorption, ion exchange, chemical precipitation and oxidation (WHO, 2011).

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Wastewater treatment process involves the removal of solids and processing of the solids prior to final disposal. The characteristics of the removed solids is of particular importance due to the constituents present in the wastewater, i.e. organics, nutrients, pathogens, metals and toxins. The sludge generated from the Darvill WWTW is of particular importance due to the close proximity of the Darvill sludge land to the Msunduzi River, which poses a risk of water contamination.

The sludge removed during treatment of wastewater is processed and ultimately disposed by means of spraying on the Darvill sludge land, and then subsequently removed by means of grass planting that is regularly harvested for instant lawn. The sludge that is generated during the treatment process at the Darvill sludge land is sampled and tested for the concentration of heavy metals present, i.e. As, Cd, Cr, Cu, Pb, Hg, Ni and Zn. Soil from the Darvill sludge land is also sampled and tested for the aforementioned heavy metals in order to monitor compliance with the Guidelines for Utilisation and Disposal of Wastewater. The Guidelines for Utilisation and Disposal of Wastewater were developed to enable beneficial use of sludge without harming the environment. Limits have been set for metals present in the soil in order to ensure that the soil quality does not degrade to a point where remediation would be necessary.

This study was aimed at meeting the objectives set out in the beginning of the study, namely, to assess the sludge disposal method currently employed at Darvill WWTW against the current and future design flow. This objective was achieved as can be seen from the results and discussions thereof presented in Chapter 4 of this study.

A combination of field tests and desktop study was used in the successful completion of the research report. Field tests were conducted to determine the amount of solute retained when sludge is discharged onto the Darvill sludge land. Laboratory analyses were used to determine the soil moisture content and soil bulk density of samples from the sludge lands.

The soil samples analysed for the Darvill sludge land generally display high concentration of heavy metals for the top 200mm of soil and thereafter decrease with increasing depth. From the 5 sample locations investigated only 1 sample location fully complied with the Guidelines for Utilisation and Disposal of Wastewater Sludge in terms of the average heavy metal concentration present in the soil.

The amount of solute that is retained by the soil when discharging of sludge takes place is higher for the top 200mm of soil and it decreases with increasing soil depth. The projected concentration of heavy metals present in soil over a 10 year period follows a similar trend to that of the amount of solute retained.

As mentioned previously in the report, the sludge removed during treatment of wastewater at the Darvill WWTW is processed and ultimately removed by spraying onto the Darvill sludge land, and then subsequently removed by means of grass planting that is regularly harvested for instant lawn. The harvested grass is sold commercially for uses such as road verges, grassing of sports fields, and landscaping by property developers or individuals.

The use of instant lawn with a high heavy metal concentration and a high nutrient load can have a negative impact on the environment. The release of heavy metals and nutrients into water bodies such as lakes located on property developments or rivers in close proximity to roads by means of surface runoff can cause health and environmental problems.

It is therefore important to ensure that a soil sample from harvested grass for instant lawn is tested to ensure that the amount of heavy metals and nutrients present is not excessive. In addition to this, the amount of heavy metal and nutrient present in the soil must be disclosed to the buyer, the harmful effects of such nutrients and heavy metals when released into water bodies as well as mitigation measures that can be adopted to minimise the harmful effects of such heavy metals and nutrients when released into the environment.

Out of the 8 monitoring boreholes for the Darvill WWTW, 7 boreholes comply with the South African Water Quality Guideline for Nitrate, and it was also noted that the sampling frequency of these monitoring boreholes does not comply with the guidelines, i.e. samples to be taken every 3 months.

If nothing is done, the soil quality at the Darvill sludge land will continue to deteriorate. It is also noted that the current soil quality does not fully comply with the Guidelines for Utilisation and Disposal of Wastewater (Volume 4) which is intended to enable beneficial use of sludge without harming the environment.

5.2 Potential use of research report

In chapter 2 it was mentioned that constituents present in the sludge generated during the treatment process have negative impacts on the receiving environment if it is not properly treated and disposed. WWTWs like Darvill WWTW frequently sample sludge to be discharged and the receiving environment for compliance with the guidelines for utilisation and disposal of wastewater sludge but very seldom project the potential future concentration of heavy metals present in the soil. This approach enables the plant operator to adopt mitigation measures to reduce the impact of non-compliance as opposed to waiting for the concentration of heavy metals to exceed the MPLs and thereafter putting measures in place to deal with the potential problems.

The simple model presented in this research report will enable individuals to project the concentration of heavy metals to be expected in the soil based on the amount of solute retained. As with many models, there are certain limitations and gaps which can be viewed as an opportunity for further investigation. For this particular research report the limitations and assumptions made have been summarised in chapter 4.

The technique adopted for this model was to model the worst case scenario so as to determine the concentration of heavy metals in soils over a 10 year period. A more advanced model can be developed to take into account the following:

- Effects of removal of grass by means of instant lawn and the effect this has on the concentration of heavy metals in the topsoil.
- Potential mobility of the heavy metal through the soil and the potential adsorption of heavy metal resulting in the decrease in concentration.

5.3 Recommendations

- Industries discharging industrial effluent into the sewage disposal system must ensure compliance with the Water Services Bylaws of Msunduzi Municipality, i.e., ensure that permission to discharge industrial effluent is granted by the municipality, ensure compliance with the discharge limits by regularly testing their effluents, enforcing the provision of preliminary treatment in order to reduce the concentration of heavy metals present in the industrial effluent. Any person who is found to be in contravention to the set discharge limits is to have their permit withdrawn, and in addition to this shall be fined and/or be subject to prosecution depending on the severity of the offense.

- Umgeni Water to work together with Msunduzi municipality to reduce/eliminate the ingress of stormwater into the wastewater collection system. This can be done by the removal of illegal direct connections (diversion of roof guttering and stormwater into the sewer system) and the reduction in quantity of stormwater ingress into the wastewater collection system by means of maintenance and rehabilitation of wastewater collection systems. The continuous monitoring and enforcement of the abovementioned is to be implemented to ensure sustainability. An awareness program by means of engaging the community to educate them about the importance of minimising stormwater ingress into sewer systems is a method that can be implemented. This will ensure the reduction of illegal direct connections. UW can also launch education campaigns targeting schools in Pietermaritzburg to inform learners about the negative impacts of illegal direct connections and stormwater ingress on the sewer system.

- Engineers are to design sewer manhole covers using material which is less susceptible to vandalism and theft, i.e., the use of concrete or glass reinforced plastic (GRP) manhole cover as opposed to the traditional steel manhole cover which is often removed and sold at scrapyards. This requirement can be incorporated into the standard design specification to ensure compliance.

- UW to ensure continuous collection and analysis of groundwater from the monitoring boreholes located on the sludge land. Frequency of sampling and the groundwater analyses to be conducted should comply with table 25 of the Guidelines for the

Utilisation and Disposal of Wastewater Sludge: Volume 4 (2006). This will allow for early detection of potential contamination of Msunduzi River as a result of the excessive concentration of NO_3. In an attempt to protect the groundwater from contamination the current and future projected contaminant concentrations may need to be estimated. The fate and transport of nutrients and heavy metals can be modelled to estimate the contaminant concentration over time, which can be compared to the maximum allowable concentration in order to protect the environment.

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ANNEXURE

List of annexures

Annexure A: Darvill sludge land soil sample sites

Annexure B: Heavy metal concentration of soil sample 9, 12, 15 and 24.

Annexure A

Darvill sludge land soil sample sites

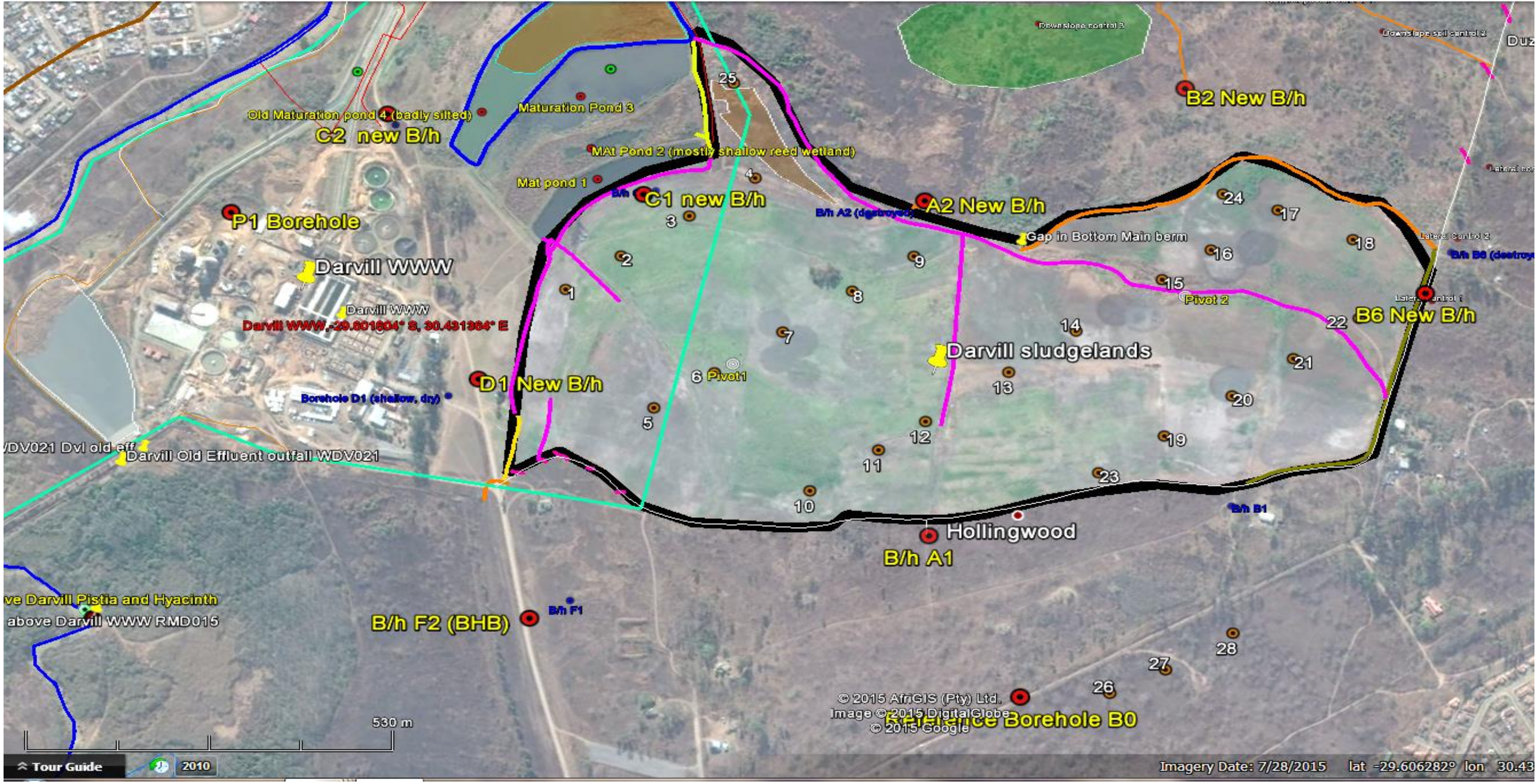
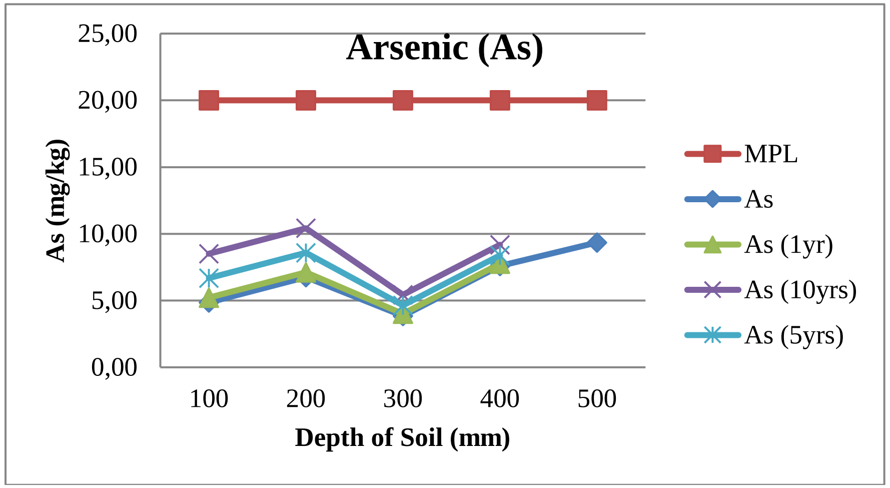
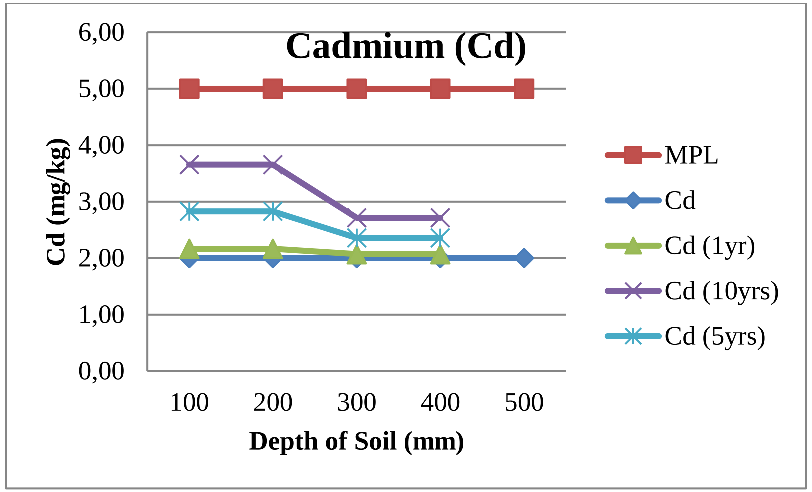


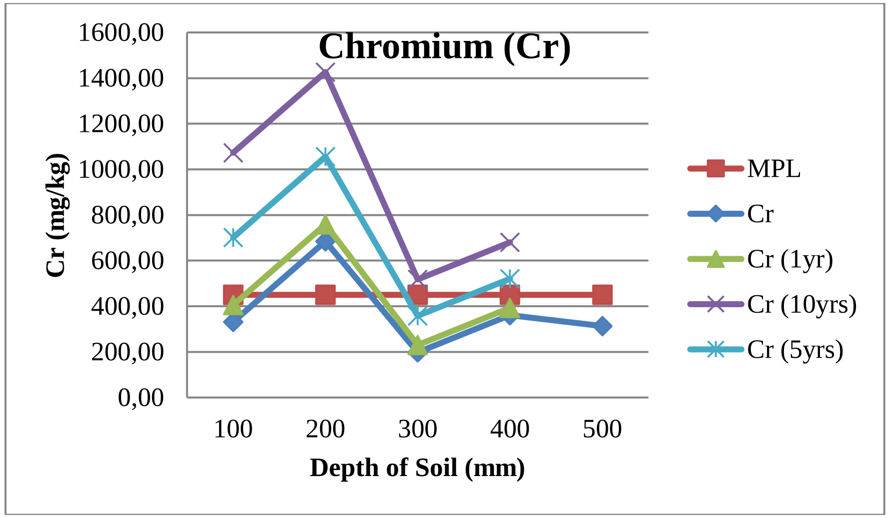
Figure A-1: Darvill sludge land soil sample sites.

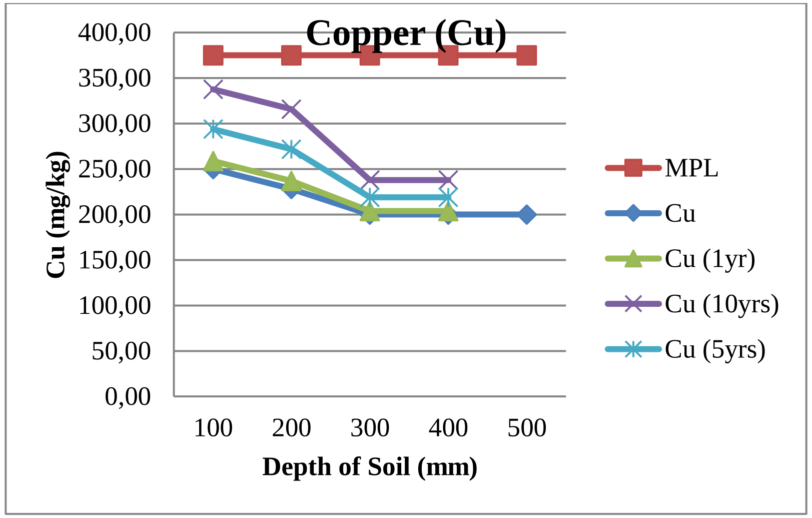
Annexure B

Heavy metal concentration of soil sample 9.









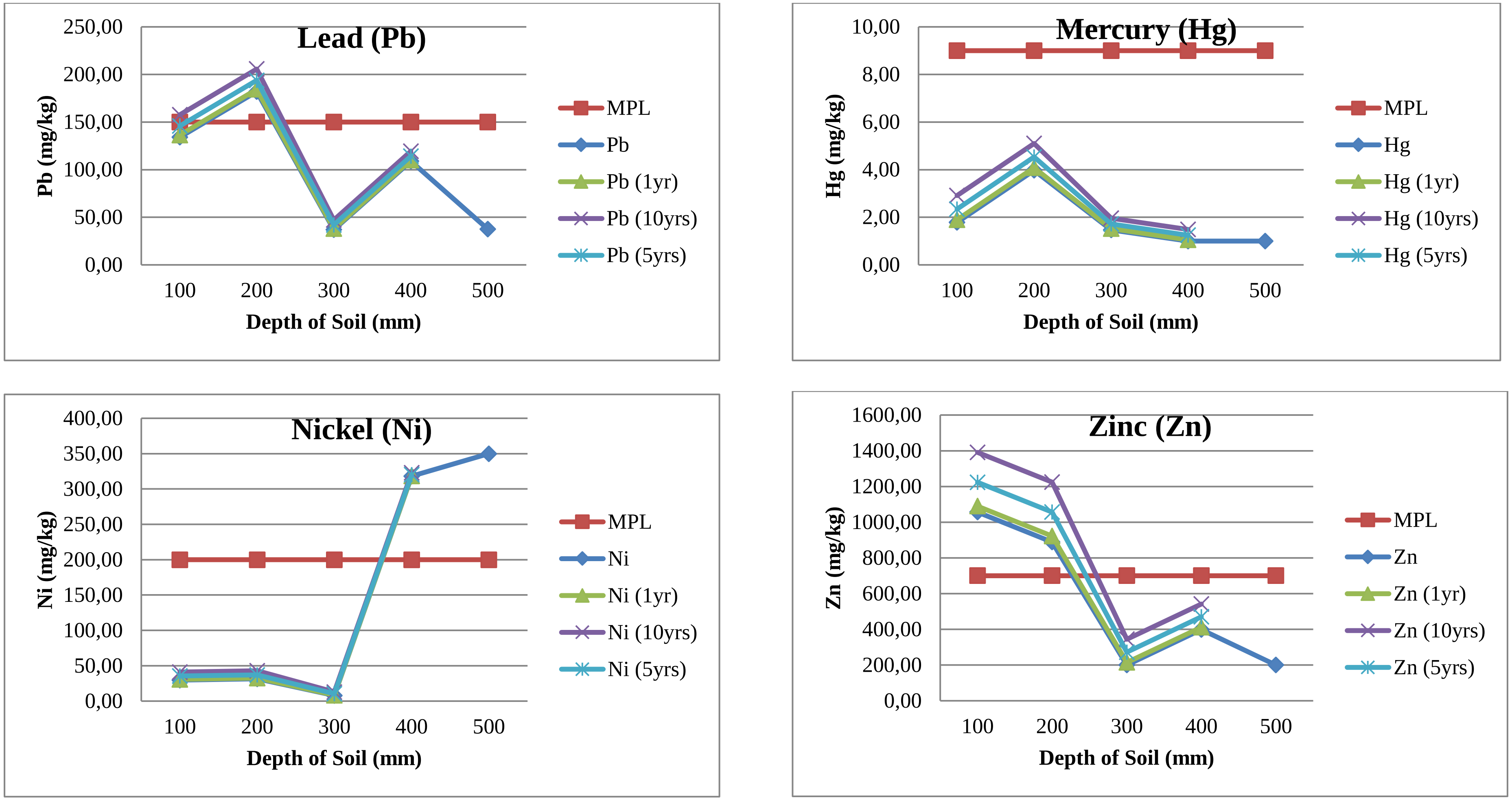
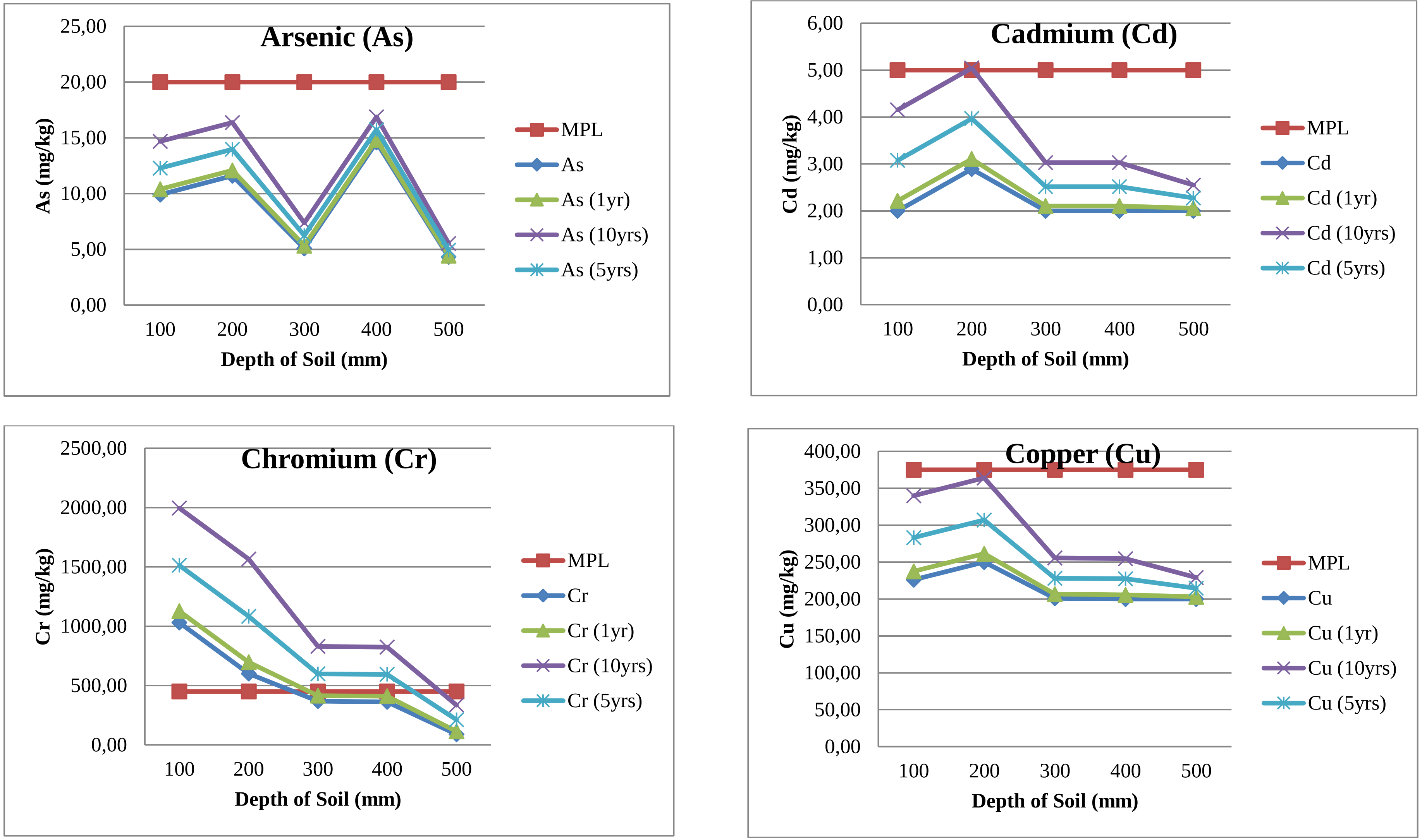


Figure B-1: Heavy metal concentration of soil sample 9.

Heavy metal concentration of soil sample 12.



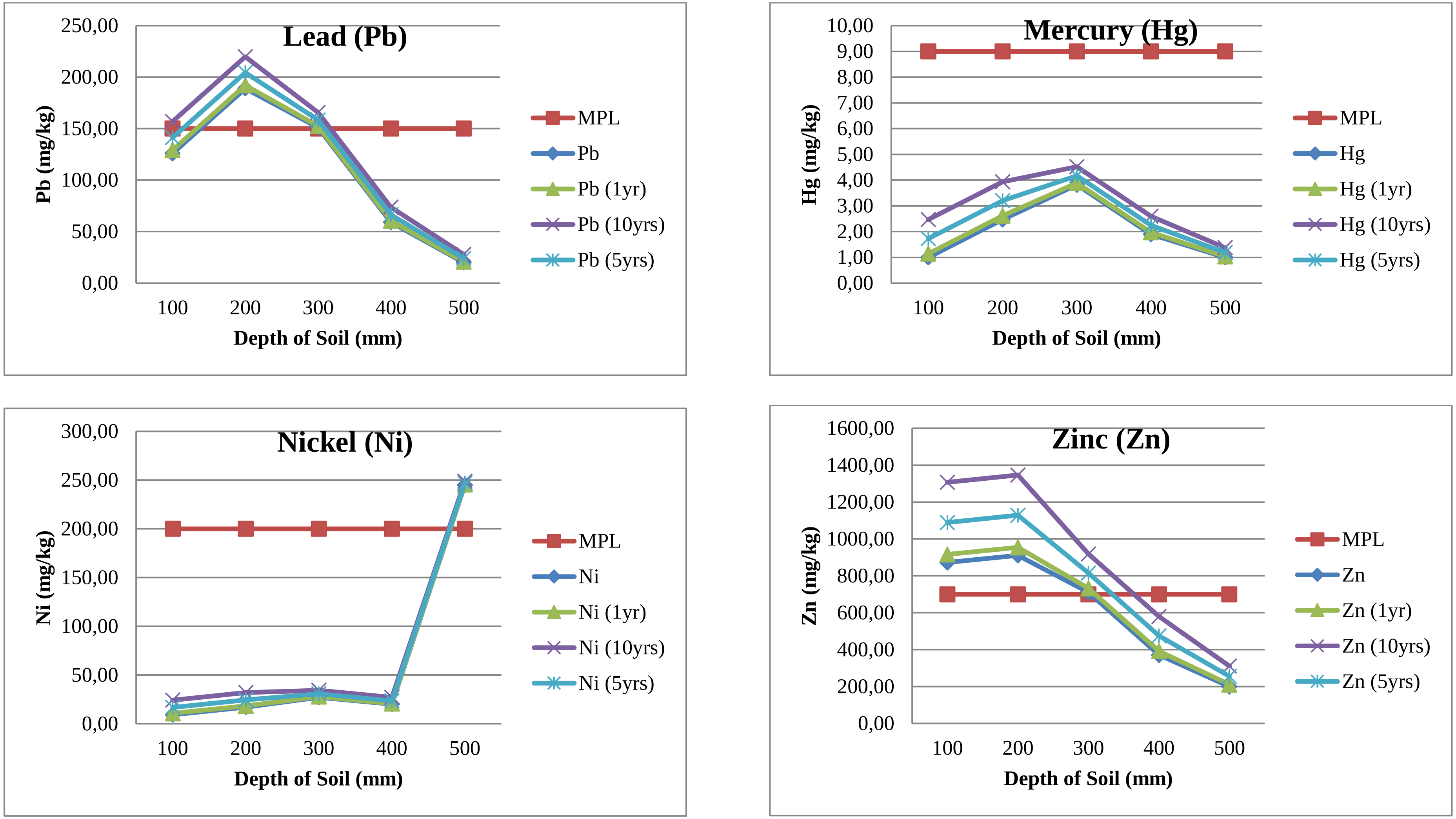
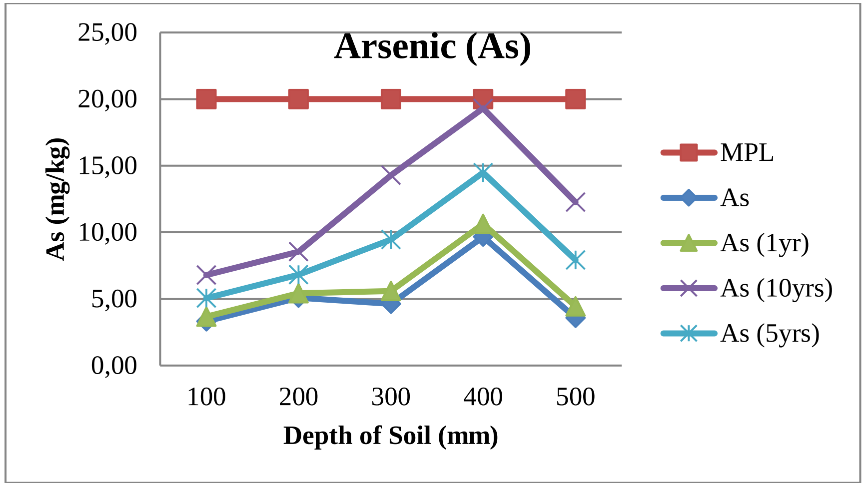
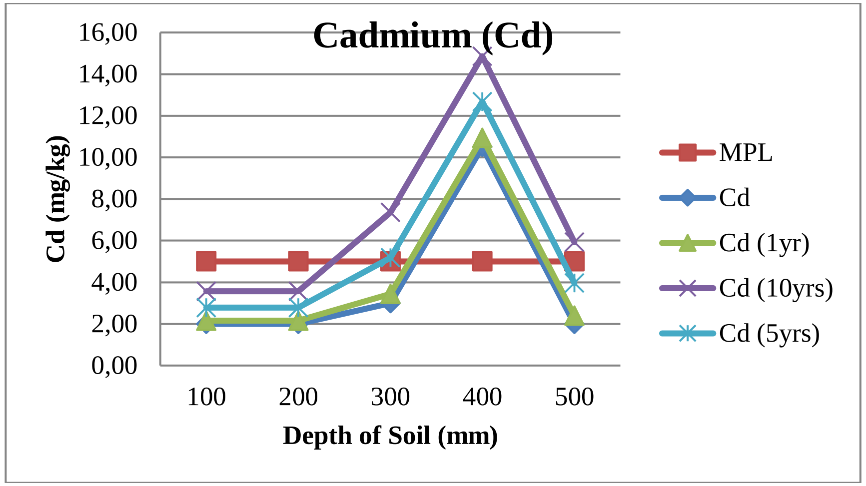
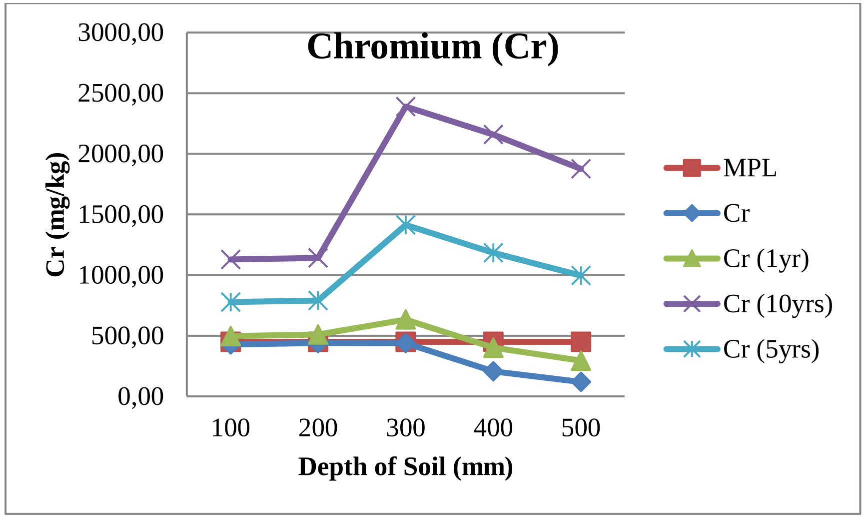


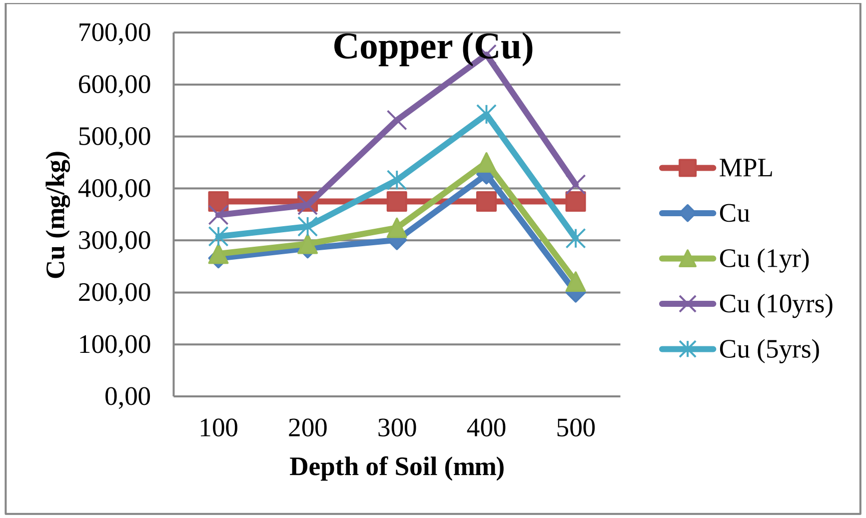
Figure B-2: Heavy metal concentration of soil sample 12.

Heavy metal concentration of soil sample 15.


Arsenic (As)
As (mg/kg)
25,00
20,00
15,00
10,00
5,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
As
As (1yr)
As (10yrs)
As (5yrs)


Cadmium (Cd)
Cd (mg/kg)
16,00
14,00
12,00
10,00
8,00
6,00
4,00
2,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
Cd
Cd (1yr)
Cd (10yrs)
Cd (5yrs)


Chromium (Cr)
Cr (mg/kg)
3000,00
2500,00
2000,00
1500,00
1000,00
500,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
Cr
Cr (1yr)
Cr (10yrs)
Cr (5yrs)


Copper (Cu)
Cu (mg/kg)
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
Cu
Cu (1yr)
Cu (10yrs)
Cu (5yrs)

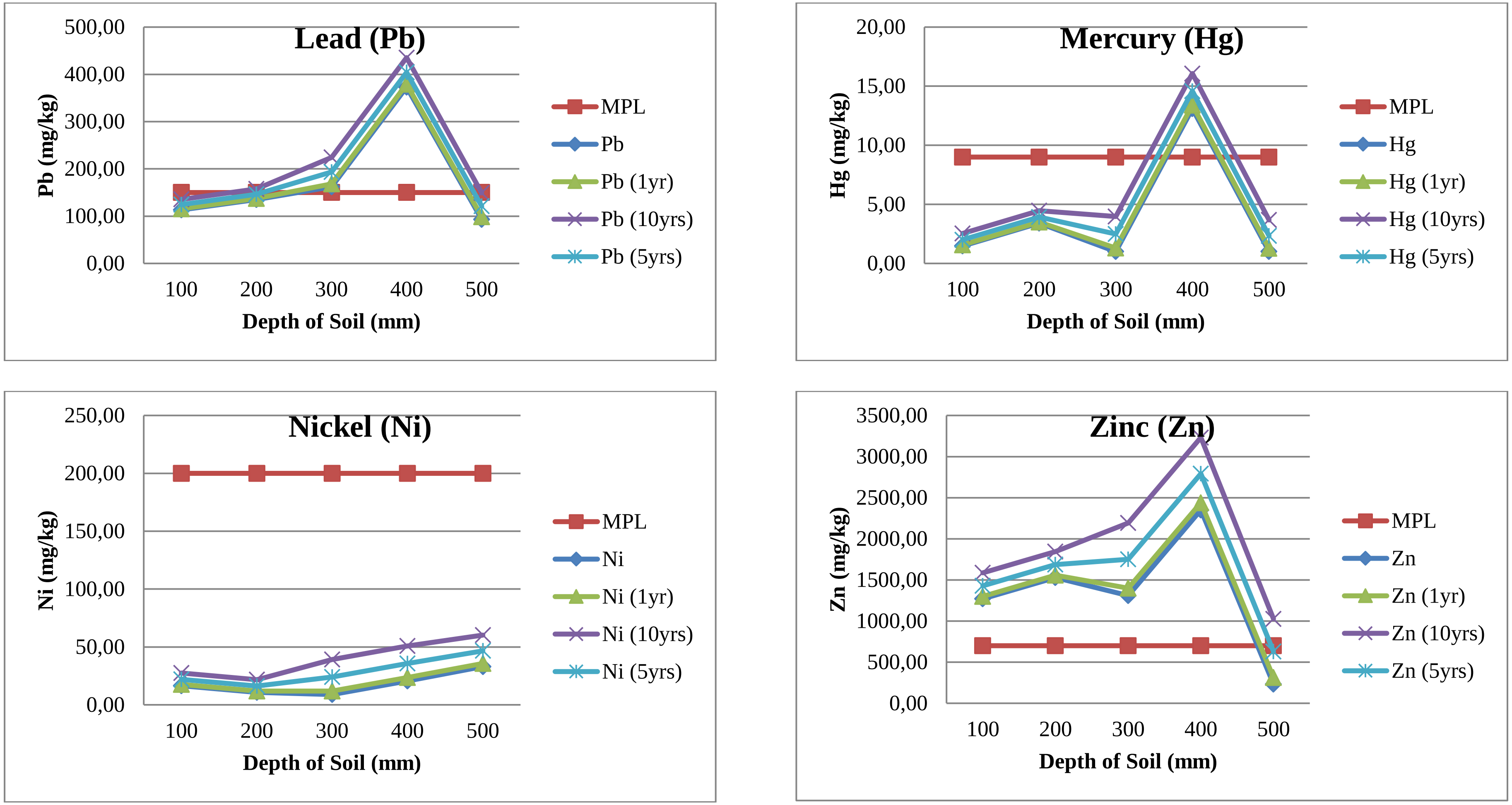
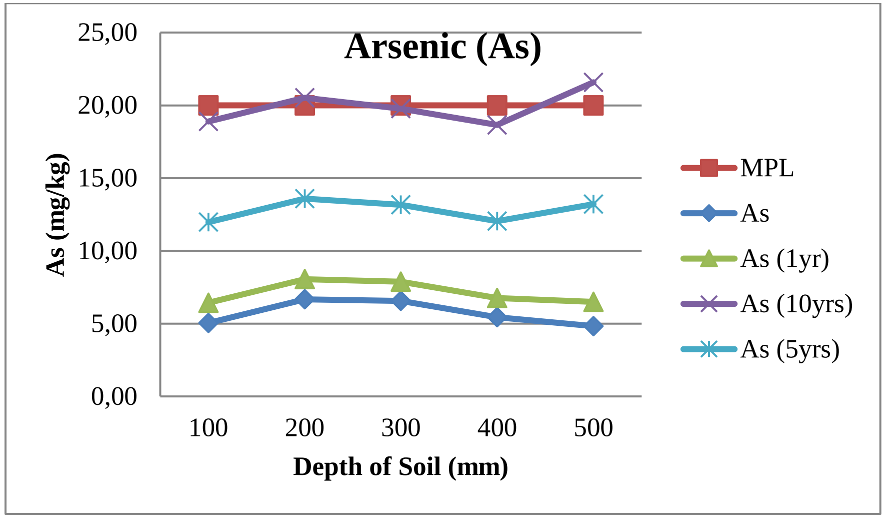
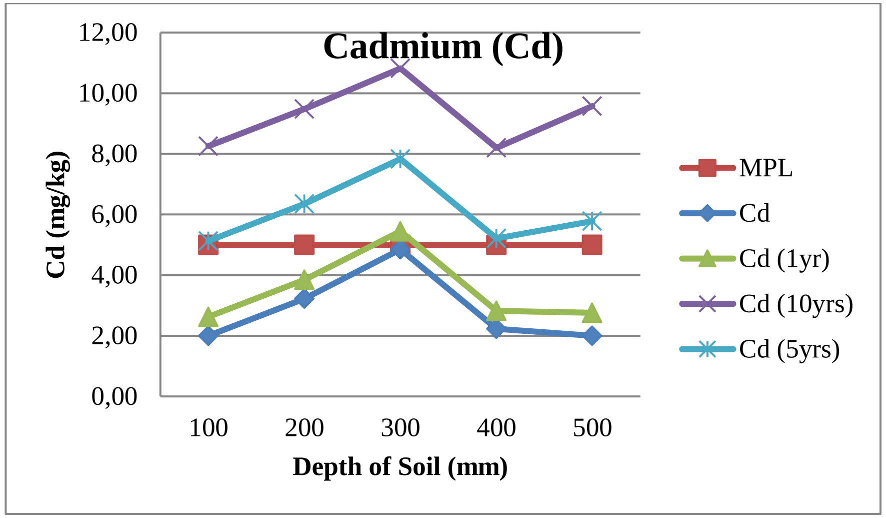
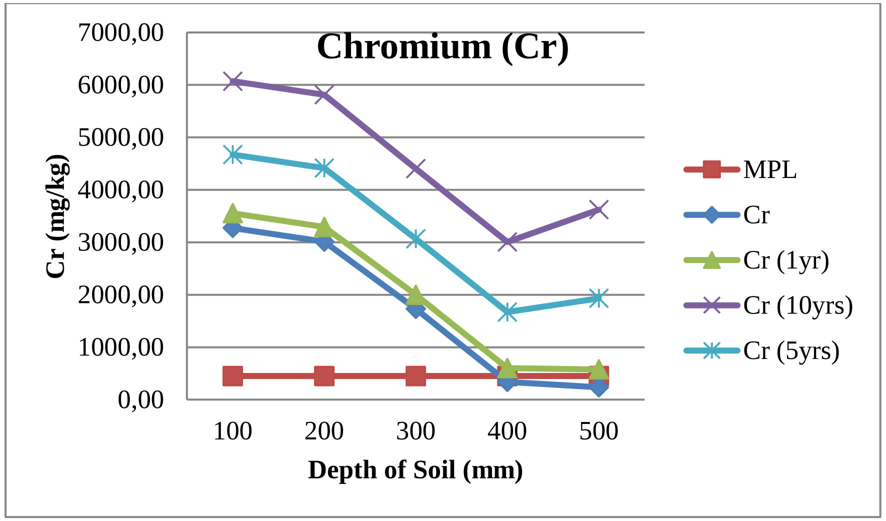


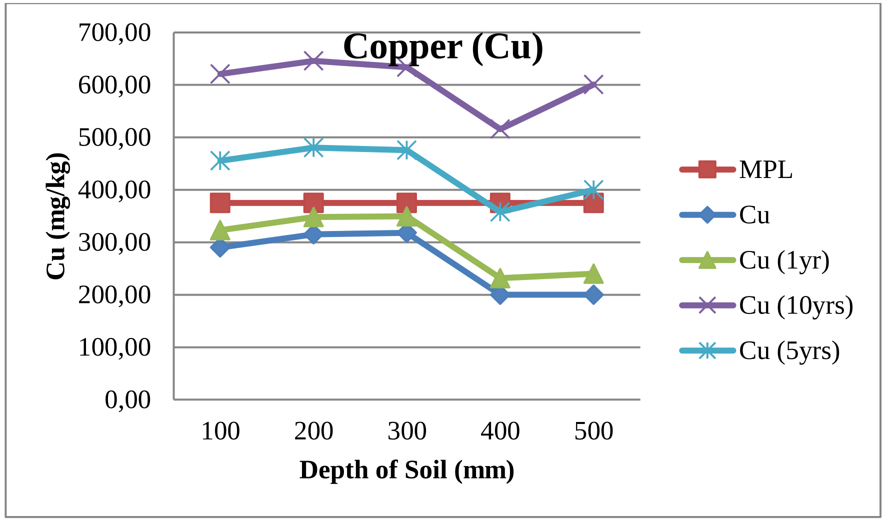
Figure B-3: Heavy metal concentration of soil sample 15.

Heavy metal concentration of soil sample 24.


Arsenic (As)
As (mg/kg)
25,00
20,00
15,00
10,00
5,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
As
As (1yr)
As (10yrs)
As (5yrs)


Cadmium (Cd)
Cd (mg/kg)
12,00
10,00
8,00
6,00
4,00
2,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
Cd
Cd (1yr)
Cd (10yrs)
Cd (5yrs)


Chromium (Cr)
Cr (mg/kg)
7000,00
6000,00
5000,00
4000,00
3000,00
2000,00
1000,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
Cr
Cr (1yr)
Cr (10yrs)
Cr (5yrs)


Copper (Cu)
Cu (mg/kg)
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
100
200
300
400
500
Depth of Soil (mm)
MPL
Cu
Cu (1yr)
Cu (10yrs)
Cu (5yrs)

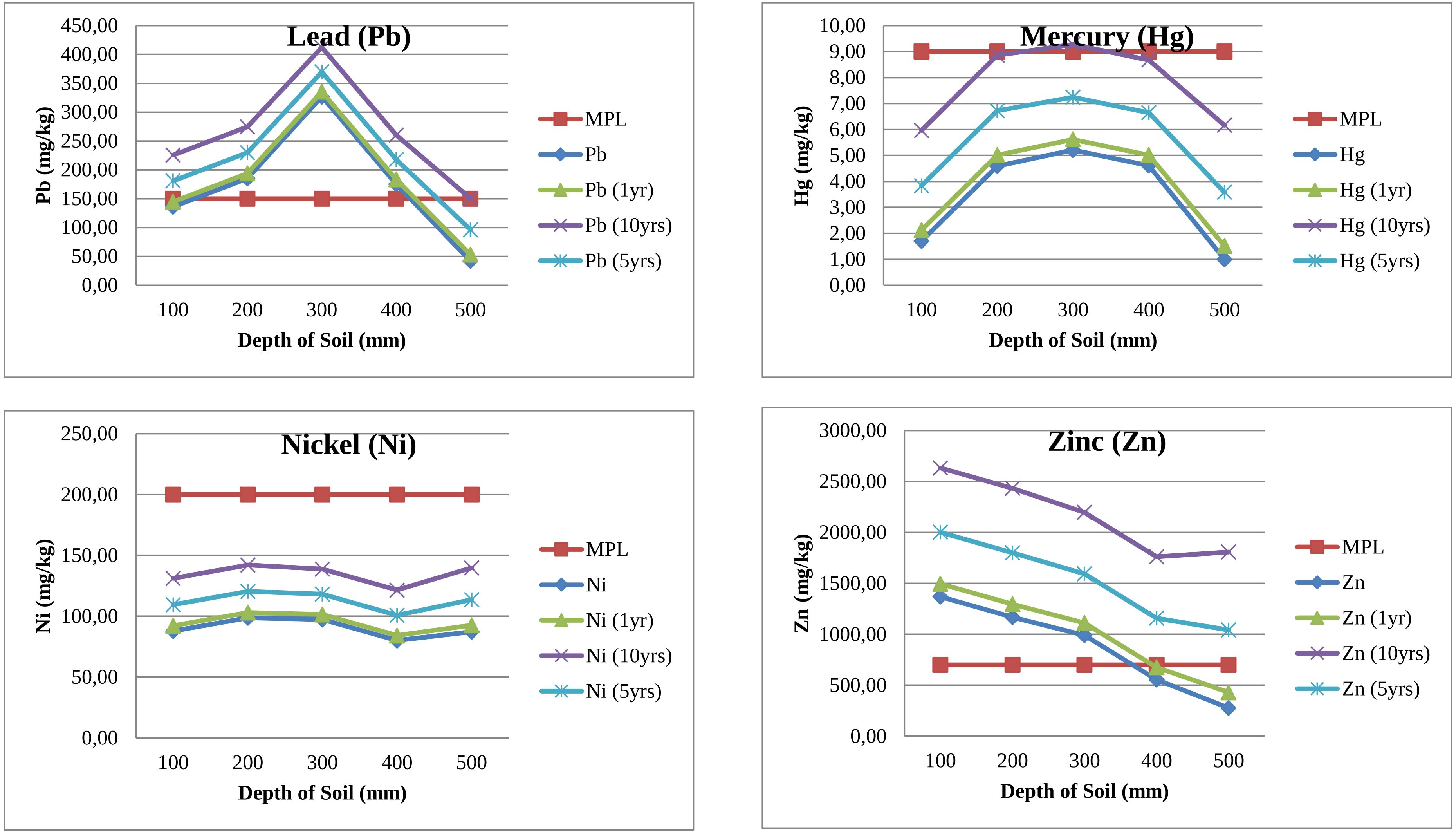


Figure B-4: Heavy metal concentration of soil sample 24.