Quality assessment of sludge from Glen Valley wastewater treatment plant and its potential as fertilizer

by

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Preface

This report is the final part of our Master thesis project and Master of Science in Environmental Engineering at Lund University. The thesis has been performed at the Water and Environmental Engineering at the Department of Chemical Engineering and in cooperation with University of Botswana. The work was carried out during the spring 2015 which of nine weeks were spent in Botswana.

First of all we would like to thank our supervisor in Sweden, associate professor Karin Jönsson, for all help and support throughout the project. Thanks to Karin we got the opportunity to work with this project. We also want to express our warmest thanks to our supervisors in Botswana; Dr. Philemon Odirile and Dr. Veronica Obuseng. Thank you for all your great care and support during our stay in Botswana.

We would also like to express our warmest appreciations for all the staff working at the Water Utilities Corporation in Gaborone. We are grateful that you let us analyze the quality of sludge from Glen Valley wastewater treatment plant, and thank you for introducing us to your work with sludge management. We especially want to thank Ms. Motoma in the Effluent Agreement group for introducing us to the work with source tracking in Gaborone. Thanks to Ms. Monametsi and Mr. Sagothusi for answering all our questions about sludge quality and to Ms. Madilola for introducing us to the work with sludge management in Gaborone. Our greatest appreciation goes also to Mr. Garkwe for showing us around at the Glen Valley wastewater treatment plant.

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Many thanks also to the staff at Water and Environmental Engineering at the Department of Chemical Engineering at Lund University. First of all, we want to show our appreciation to our examiner, research associate Åsa Davidsson. We also want to say thank you to professor Jes la Cour Jansen for being supportive and engaged in our project, answering many

of our questions and helping with contacts. Thanks also to our friend, laboratory assistant Gertrud Persson for the consultation and assistance with safety equipment for our field study and sludge sampling.

We would also like to thank the Biological Department at Lund University for the help with the nutrient and heavy metal analysis of the sludge samples from Glen Valley wastewater treatment plant. Without these results it would not have been possible to have a clear understanding and estimation of the status of the sludge.

Thanks to Dr. Linda Önnby at the Division of Biotechnology at the Department of Chemistry for introducing us to heavy metal analysis concepts and research in other countries.

We would also like to thank our mentor Sten Stenbeck for all your inspirational advices and recommendations of sights and attractions to see and visit around Gabs. Your tips were decisive for our fantastic experience of Botswana.

Furthermore, we also want to thank our families and friends who supported us in this project. Thanks to Hanna Palm Johansson and Elin Andersson who have not only have been wonderful office colleagues at Lund University, but also travel companion and supporters in Botswana.

For making the thesis economically possible, we also want to thank SIDA and Ångpanneföreningens Forskningsstiftelse.

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Ellen Åberg and Johanna Norup

Abstract

The use of sludge as fertilizers contributes to the recycling of nutrients to the environment due to its origin from wastewater and therefore relatively high content of nutrients and organic matter. However, wastewater does also contain hazardous compounds like heavy metals and micropollutants which eventually are separated to the sludge during the treatment processes at the wastewater treatment plant. In order to improve the sludge quality, source tracking is a relatively cheap and effective way to find and eliminate hazardous compounds and prevent them from ending up in the sludge.

The aim with this thesis was to investigate the fertilizer potential in sludge from Glen Valley wastewater treatment plant (GWWTP) in Gaborone, Botswana. The sludge is analyzed in terms of nutrient and heavy metal contents as well as physiochemical parameters. In order to determine the potential as fertilizer, the quality of the sludge is compared with other fertilizer alternatives, other sludge types and regulations for sludge use in agriculture. The work with sludge quality improvements in Gaborone is also investigated. Sludge from different stages along the treatment processes were collected in order to see differences in quality related to the treatment.

The results shows that the samples of primary anaerobically treated sludge tend to have higher heavy metal content than the secondary sludge. The quality of the dry sludge samples indicates lower nutrient content than both the primary and secondary sludge, but similar heavy metal content. The analysis of dry sludge from GWWTP indicates a low nutrient value and high heavy metal content in comparison to other selected fertilizer options and sludge from other WWTPs. The processes for removal of nutrients from the wastewater are an important factor for the nutrient content in the sludge.

The sludge from GWWTP is currently sold as fertilizer and soil conditioner. In order to get a sustainable sludge production and a safe fertilizer alternative, a clearer strategy for the management and analysis of the sludge could be established. There is no found legislation of sludge quality for agricultural use in Botswana but it was found that arsenic, copper, lead and zinc exceeded the limits according to the South African regulations that are likely to be implemented in Botswana in the future. The Swedish limits were exceeded for lead and zinc.

The work with source tracking in Botswana is conducted in the Trade Effluent Agreement (TEA) where the strategy is to make an agreement with industries to only discharge wastewater to the sewer system that is approved by the country's water authority. There is a challenge in getting industries to participate in the agreement.

The result from this thesis is only based on one single sampling occasion. A continuous and more frequent sludge quality analysis work must be done in order to determine the actual potential as fertilizer. The result presented in this report does though indicate that the quality of the sludge needs to be improved before it can be assured that the sludge is safe and sustainable to use as fertilizer for food production.

Keywords: Sewage sludge, fertilizer, nutrient recovery, nutrients, heavy metals

Sammanfattning

Avloppsslam innehåller viktiga näringsämnen och organiskt material för planttillväxt som kan återvinnas till jordbruket genom att använda slammet som gödningsmedel. Men avloppsslam innehåller också miljöfarliga ämnen som tungmetaller som i avloppsreningsprocessen separeras till slammet. För att förbättra kvaliteten av avloppsslam kan därför uppströmsarbete göras - en relativt billig och effektiv metod för att finna och eliminera farliga föroreningar som annars hamnar i slammet.

Syftet med detta examensarbete är att undersöka potentialen för att använda slam från Glen Valley’s avloppsreningsverk (GWWTP) i Gaborone, Botswana, som gödningsmedel. Slammet analyserades med avseende på näringsämnen och tungmetaller samt fysiokemiska parametrar. För att se skillnader i kvalitet med avseende på reningsprocesser togs prover från fem olika punkter längs med processerna på avloppsreningsverket. För att bestämma gödselpotentialen jämfördes slamkvalitén med andra gödningsmedel och slam men också med gränsvärden från olika länder för slamkvalité vid gödsling. Arbetet med kvalitetsförbättring av slam i Botswana och speciellt uppströmsarbete undersöks också i arbetet.

Resultatet från studien visar att primärslammet har högre tungmetallhalt än sekundärslammet medan näringsinnehållet är likvärdigt. Proverna från de torra slammen visade lägre näringsinnehåll än både primär- och sekundärslammet, medan tungmetallsinnehållet var likvärdigt.

Jämfört med andra gödningsmedel och andra slam visade det torra slammet från GWWTP på ett relativt lågt näringsvärde men högt tungmetallinnehåll. Detta skulle kunna förklaras av ursprunget och karaktären av avloppsvattnet. Processer som används på avloppsreningsverk har också stor betydelse för andelen näringsämnen i slamfasen.

Slam från GWWTP säljs redan idag som gödningsmedel och jordförbättringsmedel. För att få en mer hållbar slamproduktion och ett säkert gödningsalternativ krävs dock en tydligare strategi för hantering och kvalitetsanalys av slammet. Det finns för närvarande ingen lagstiftning rörande slamkvalitet för jordbruksanvändning i Botswana. Istället jämfördes slamkvalitén med utvalda gränsvärden från olika länder varpå arsenik, koppar, bly och zink överskrider gränsvärdena för tungmetallinnehåll i Sydafrika som troligtvis kommer implementeras i Botswana i framtiden. Endast halterna av bly och zink överskrider de som tillåts i den svenska lagstiftningen.

Arbetet med uppströmsarbete i Botswana innefattas i Trade Effluent Agreement (TEA). Strategin för överrenskommelsen är att komma överens med industrier att endast släppa ut sådant avloppsvatten till ledningsnätet som är godkänt enligt landets vattenmyndighet. Det finns utmaningar med att få industrier att delta i överrenskommelsen.

Resultatet av slammets kvalitet från GWWTP är i denna rapport endast baserat på en provtagning. En kontinuerlig och mer frekvent slamkvalitetsanalys måste göras för att fastställa den aktuella gödselpotentialen i slammet. Resultatet indikerar dock att den nuvarande kvaliteten av slammet behöver förbättras för att försäkra en säker och hållbar gödselanvändning av slammet för livsmedelsproduktion. Ytterligare studier för att förbättra gödselpotentialen av slam från GWWTP presenteras också i denna studie.

Nyckelord: avloppsslam, gödningsmedel, näringskretslopp, näringsämnen, tungmetaller

Glossary

Blackwater – Wastewater stream originating from the toilet: urine, feces, toilet paper

BOD – Biochemical Oxygen Demand

COD – Chemical Oxygen Demand

Digestate –by-product from biogas production

DWA – Department of Water Affairs

Greywater – Wastewater originating from e.g. washing, showers, baths

GWWTP – Glen Valley wastewater treatment plant

Manure – Animal feces

MMEWR – Ministry of Mining, Energy and Water Resources

NAMPAADD – National Mater Plan for Agriculture and Diary Development

PE – Person Equivalents

PHA – Polyhydroxyalkanoates

TEA – Trade Effluent Agreement

TS – Total Solids

VFA – Volatile Fatty Acids

VS – Volatile Solids

WUC – Water Utilities Corporation

Table of Contents

1 Introduction

This chapter introduces the thesis with a background, aim, objectives with questions and limitations.

1.1 Background

The use of fertilizers in agriculture has for a very long time improved the life situation for people all over the world because of increased crop growth. However, as the population increases, the demand for food and fertilizers is also increasing (Cordell *et al.*, 2011). The way that nutrients for fertilizer are extracted and used today is not sustainable in all manners and there is a great need of finding innovative solutions for returning nutrients to the agriculture.

There are several different types of fertilizer products used on the market today; artificial fertilizers, manure, digestate from biogas production and sewage sludge for example. Still a fertilizer must be able to meet certain requirements in order to be used on the agricultural market. The main requirements for a fertilizer is that it should contain high content of plant nutrients like nitrogen, phosphorous, potassium etc., and also be free from hazardous compounds and heavy metals (Ljung, *et al*., 2013; Petersson, 2008). In addition to this, it is also desirable that the fertilizer will improve the soil structure and be convenient to handle with the current used agricultural machinery (National Gardening Association, 1999; Ljung *et al*., 2013; Levlin *et al*., 2014).

The nutrients in artificial fertilizers are extracted from natural resources; phosphorous from phosphate rocks and nitrogen from airborne N_2 with the input of energy and water (The Fertilizer Institute, 2002; Levlin *et al*., 2014; Socolow, 1999). Approximately 90% of the world's resources of phosphorous can be found in sedimentary rocks (Linderholm, 2011; Finnson, 2013). However, the production is about to reach its peak. According to Cordell *et al.* (2009), phosphorous from phosphate rocks is estimated to end within 50-100 years and that peak phosphorus is likely to occur before 2035. This is the time when the more than half of the available phosphorous is extracted. Humanity is therefore facing a great challenge.

The use of sludge as fertilizer is an efficient and sustainable alternative to bring back nutrients to the agriculture and environment. Sludge is a by-product from the wastewater treatment plant and consists of separated solid organic and inorganic matter originating from the incoming wastewater. Sludge is produced through mechanical, biological and chemical processes at the wastewater treatment plant where solids in wastewater can be eliminated from the liquid stream and separated to the sludge (Hammer & Hammer, 2014; Wang *et al*., 2006; Lidström, 2013).

However, sewage sludge may also contain hazardous compounds such as heavy metals, micropollutants and pathogens. These compounds can harm the human health and/or the environment. According to Duruibe *et al.* (2007), heavy metals in fertilizers spread on agricultural fields containing high contents of heavy metals tend to bioaccumulate in plants and further to animals and humans.

There are many ways to improve the sludge quality. Apart from treatment techniques like struvite enhancement, activated carbon treatment and combustion, source tracking is an efficient and relatively cheap method to trace and eliminate hazardous compounds and heavy metals from the sludge and also from the effluent stream (Sanin *et al.*, 2011). This can for example be done by imposing requirements for the use of particular substances, regulate the connections to the sewer network, or by introducing additional treatment processes at the industry (NSVA, 2015).

In this thesis sludge and sewage sludge is defined as the by-product from a wastewater treatment plant if nothing else is written.

1.1.1 Wastewater and sludge in Gaborone

Glen Valley wastewater treatment plant (GWWTP) treats Gaborone's wastewater with a capacity of 90 ML/day. The incoming stream consists of both domestic and industrial wastewater but also an added amount of sludge from pit latrines around the city. Gaborone is not a heavily industrialized city but the main industries are breweries and abattoirs, but also pharmaceutical, painting and chemical industries that discharge their wastewater into the sewer network exist (Nkegbe & Koorapetse, 2005). The wastewater undergoes both primary and secondary (biological) treatment where both primary sludge and secondary sludge are formed. The sludge is treated in a sludge treatment plant built in 2009/2010. The treated sludge is stored in piles from where it is sold to local farmers and individuals, see chapter 6 (Garekwe, 2015).

Gaborone is suffering from severe water scarcity where a lot of emphasis is placed on solving this challenge. Due to this, the local water authority WUC has not been able to focus on the treatment and management of sewage sludge until the latest years. At the moment there are no known quality and quantity control of the sludge at GWWTP (Waves technical report, 2014; Garekwe, 2015). There is neither legislation nor guideline in the country regulating the quality of sludge used in agriculture.

During the past years, the agricultural sectors contribution to the country's national economic growth has decreased in Botswana. Since droughts are becoming more common, and as the crop production is dependent on rainfalls; agriculture is a high risk business (UNDP, 2012). This reason among others makes it important to find cheap and sustainable ways to produce food in the county. According to Morris & Kelly (2007), there is a great demand of finding cheap alternatives to artificial fertilizers in Africa.

1.2 Aim

The aim with this master thesis project was to assess the fertilizer potential of sludge from Glen Valley wastewater treatment plant. The project were highlighting the current status of the sludge produced at GWWTP with focus on heavy metals and nutrient content and also possible improvements to get a nutritious and harmless sludge, both in environmental and health aspects.

1.3 Objective

By determining the sludge quality of Glen Valley wastewater treatment plant, the health and environmental risks with the use of sludge in agriculture can be estimated. The objective is therefore to: 1) assess the quality of sludge from GWWTP in terms of heavy metals, nutrients and physiochemical parameters, 2) analyze the sludge treatment processes, management and use of produced sludge at the plant, 3) Investigate possible improvements for the quality of the sludge from GWWTP.

1.4 Questions

The questions that will be addressed in this study are:

1. What is the quality of the sludge from Glen Valley WWTP in terms of nutrient and metal content as well as physiochemical parameters?

2. How is the sludge handled at GWWTP today, and what is it used for?

3. Can the sludge from GWWTP be used as fertilizer in terms of regulations for sludge use, treatment processes, other fertilizers and agricultural requirements?

4. What is done today and what possible actions can be made in the future for improving the fertilizer potential of sludge from GWWTP?

1.5 Limitations

This chapter describes limitations of the report and what boundaries that have been made in order to answer the objectives of the thesis. The chapter is divided in limitations in relation to the field study and comparative analysis of the sludge, but it also describes some general limitations of the thesis.

1.5.1 Field study

Samples of sludge from Glen Valley wastewater treatment plant was collected from five points, see Table 1.1. The reason for this was to find the sludge with the highest fertilizer potential. The effect of ageing on the dry sludge was also investigated by collecting sludge at different layers and therefore with different ages.

Table 1.1. Sampling points in the study.

Sample	Name	Type
1	Primary sludge	Primary sludge: Anaerobically digested
2	Secondary sludge	Secondary sludge: Aerobic digested
3	Fresh sludge	Dry sludge: Fresh
4	Old sludge	Dry sludge: Top layer of a sludge pile
5	Older sludge	Dry sludge: Bottom layer of a sludge pile

At the sampling occasion it was not possible to collect samples in the anaerobic digester whereupon the sludge was instead sampled from an open buffer tank after the secondary anaerobic digester. The sludge in the buffer tank had a retention time of approximately three weeks instead of one due to problems with the dewatering plant. To account for this, sludge was therefore collected at different levels in the tank to get a good mixture. Another limitation at the sampling occasion is that pH was not measured for the dry sludge types since there was no available instrument designed for measuring solid samples.

The sludge quality was analyzed in terms of nutrients, metals and physiochemical parameters according to Table 2.1. The analysis was restricted to those elements with respect to the availability of analytical instruments. Due to the relatively short time period of the field study, micropollutants and pathogens have not been measured in the study.

During the time of the field study there was no available instruments for nutrient analysis at the University of Botswana. The sludge samples were therefore stored for several weeks and thereafter analyzed by laboratory staff in Sweden at the Biological Institution at Lund University.

1.5.2 Comparative analysis

The result of the sludge quality is compared to some other sludge types, fertilizers and regulations. The sludge types compared are from different plants with different characteristic treatment processes. One of them symbolizes the average sludge quality from 77 different treatment plants in South Africa. This was chosen to give an idea on how different treatment methods impact the sludge quality, but it also aims to give a brief feeling of how the quality of sludge in a nearby country looks like.

The fertilizers compared to the sludge are chosen since they are the most common in Botswana. Therefore, cow manure is studied since cows are the most common cattle in the country. The artificial fertilizer was chosen since it is used for common crop production and the chosen co-digestate and blackwater values are the ones found in the literature search.

The regulations from Sweden, EU and South Africa are chosen since there are no limits in Botswana. It is likely that Botswana implements the South African regulations for different purposes, and the reason why Swedish and EU regulations are studied is because the authors are from Sweden.

1.5.3 General limitations

In this study there is only one sampling occasion. The dry sludge piles consists however of sludge from a period of time. With dispersed sampling in the pile, an average of some days up to some weeks can be found depending on the size of the sludge pile and how it is organized. The wet sludge samples give an indication of the daily variations.

The retention time of the different treatment processes is not taken into consideration in this thesis. The sludge samples collected at the different locations can therefore origin from different wastewater inflows and therefore have different characteristics.

The study focuses on conventional and centralized wastewater treatment. A significant part of the population in Gaborone use pit latrines for sanitation. The handling and use of sludge from these sanitary facilities is not discussed in a wide context.

1.6 Structure of the report

After introduction in chapter 1, chapter 2 follows with method description. It explains the procedures and sampling methods used in the thesis. Thereafter follows a literature study divided in seven chapters, starting in chapter 3 which gives a description of the studied area. Chapter 4 explains sources and properties of pollutants in wastewater. It describes pollutants in general and how they can end up in the wastewater system. Chapter 5 and 6 focus on wastewater and sludge treatment and whereupon chapter 6 describes the treatment processes at Glen Valley wastewater treatment plant. Thereafter the management and use of sludge produced at GWWTP is explained in chapter 7 where the handling system and fate of sludge is presented. Chapter 8 focuses on fertilizer requirements but also on different types of fertilizers and in particular sewage sludge. Different techniques and actions to improve the quality of sludge are presented in chapter 9 with focus on source tracking. The result from the sludge quality analysis is presented in chapter 10 and is compared to other sludge types, fertilizers and regulations in chapter 11. The result is later discussed in chapter 12. Finally follows conclusion in chapter 13 and suggestions for further work in chapter 14.

2 Materials and Methods

This study was divided into three different parts; literature study, field study and result analysis. The field study included sampling, laboratory work and interviews and the result analysis investigates the results from the field study. These three parts are described below.

2.1 Literature study

The literature study covers significant background for the determination of the fertilizer potential in the GWWTP sludge. The study was performed by studying books, articles and investigations within the field. The sources used in the literature study are mainly factual books or journal articles that have been published in scientific papers but also investigations from national authorities and wastewater treatment works.

The thesis focuses on describing the most important background knowledge about sludge and its origin, treatment processes for sludge and wastewater, improvements of sludge quality, fertilizers etc., in order to determine the potential as fertilizer. The result is compared to other sludge types, different streams at the wastewater treatment plant and other types of fertilizers. The thesis also highlights the current status and management of the sludge from GWWTP as well as general background information of Botswana. In order to get a wide comparison of the quality of sludge from GWWTP, examples and regulations from Sweden, the European Union and South Africa are highlighted. This is explained in chapter 1.5.2.

2.2 Field Study

The field study was performed both at Glen Valley wastewater treatment plant in Gaborone and at the University of Botswana. The sampling of sludge was done at the wastewater treatment plant where several interviews with staff also were done. The laboratory work was done at the University of Botswana at four different departments; the Faculty of Engineering and Technology, the Department of Chemistry, the Department of Geology and the Department of Environmental Science.

2.2.1 Interviews

The interviews were performed with staff at Glen Valley wastewater treatment plant regarding operation, maintenance, laboratory work, sewer network and administrative services. A brief description of the interviewees is presented below:

Mr. Garekwe, 16th of February

Operator at Glen Valley wastewater treatment plant. This interview is based on questions asked on a tour at the plant.

Ms. Monametsi, 5th of March 2015

Laboratory manager at Glen Valley wastewater treatment plant. The interview was about laboratory analysis and quality standards of wastewater and sludge from the plant.

Ms. Madilola, 5th of March 2015

Wastewater foreman at Glen Valley wastewater treatment plant. The interview was about sludge treatment and handling at the plant. The management and selling of sludge was also discussed.

Mr. Sagothusi, 5th of March 2015
Foreman on Pipe networks at Water Utilities corporation (WUC). The interview about the situation with sewer networks in Gaborone regarding both challenges and main focus at the moment. The Trade Effluent Agreement was also discussed.

Ms. Motoma, 11th of March 2015
Member of Trade Effluent Agreement group, Pipe networks at WUC. The interview was about the implementation of the Trade Effluent Agreement in Botswana and about the work and contacts with the industries.

2.2.2 Sludge sampling

In order to determine the quality of sludge from Glen Valley wastewater treatment plant, sludge from different stages along the process chain was sampled, see Table 2.1. The sludge was sampled from a total of five sampling points; the anaerobic digester (primary sludge), the aerobic digester (secondary sludge), on the ground outside the sludge dewatering plant (fresh sludge) and in the sludge piles both at the top (old sludge) but also at the bottom layer of the pile (older sludge). The primary and secondary sludge are defined as "wet" since $TS<10\%$ while the fresh, old and older sludge are defined as "dry" since $TS>20\%$. These points can be seen in Figure 2.1. The process scheme is further described in chapter 6. The sampling points are noted in the report as primary sludge (1), secondary sludge (2), fresh dry sludge (3), old dry sludge (4) and older dry sludge (5). The fresh dry sludge was collected on the ground after the dewatering plant and the old and older sludge was collected at random upper and lower levels respectively from one of the piles at the treatment site, see chapter 10.1.

Table 2.1. Analyzed parameters in the study.

Parameter	
Macronutrients	Tot-N, Tot-P, NO_3-N, K
Micronutrients	Mg^{2+}, Na^{+}, Ca^{2+}, SO_4^{2-}
Metals	Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn
Physiochemical parameters	VS, TS, pH, Temperature, Conductivity

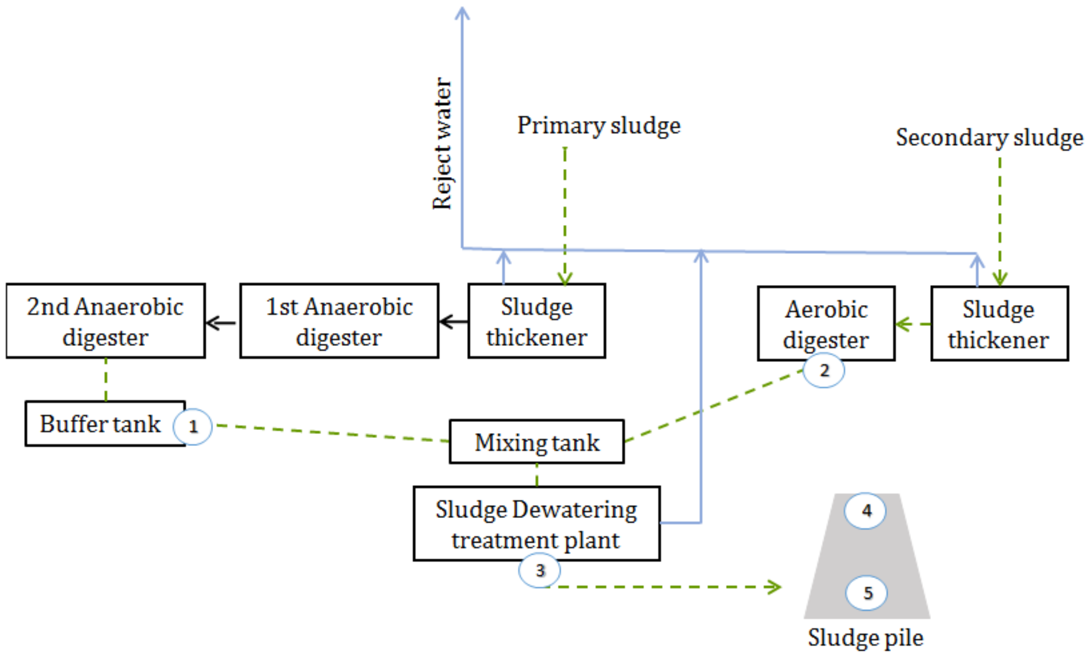


Figure 2.1. Sampling points at the wastewater treatment plant in Gaborone.

2.2.3 Sampling procedure

The sludge from each sampling point was collected in 4x1.5 L plastic boxes which directly after sampling were stored in a cooler box at the site. The samples were then stored in a refrigerator (4°C) until the day of analysis.

Depending on the consistency of the sludge and accessibility of sampling for the five different sampling points, different methods for sampling were selected: For sampling in the aerobic digester, sludge was collected with a bucket at the surface of the well mixed sludge slurry in the 5 m deep basin. The primary sludge was collected in an open buffer tank that comes after the secondary anaerobic digester. The sludge was collected with a Multi Stage Sludge Sampler at four stages within 1.2 m from the top, see Figure 2.2. The tank was approximately 4 m deep in total. All types of dry sludge (fresh, old and older dry sludge) were collected randomly at the pile by hand.

Figure 2.2 Sludge sampling from the buffer tank with the instrument Multi Stage Sludge Sampler.

2.2.4 Laboratory work

The laboratory work was done in order to determine the physiochemical parameters, nutrient content and heavy metal content of the sludge. The procedure for these determinations is stated below. The samples have been analyzed in two ways, described as B and S.

Analysis B: Performed at University of Botswana by the authors with assistance from technicians. Heavy metals and physiochemical parameters were measured.

Analysis S: Performed at Biological Institution at Lund University by laboratory staff. Heavy metals and nutrients were measured.

Below the two analysis methods are described more in detail for the different parameters measured.

2.2.4.1 Physiochemical parameters

The physiochemical parameters (pH, temperature, electronic conductivity, total and volatile solids) were determined both at the sampling site and at the Faculty of Engineering and Technology. See methodology for the above mentioned parameters below.

Electronic conductivity, pH and temperature

At the time of sampling, pH, temperature and electronic conductivity were measured only for the wet types of sludge (primary and secondary sludge). The pH was measured with ELE International 370 pH meter, the temperature with ELE International microtherma 2 digital thermometers and the electronic conductivity with ELE International 470 Conductivity meter.

Total solids (TS)

The amount of total solids in the sludge was determined by using oven ELE International heated to 105°C. A known volume of sludge was put into a beaker with a known weight. The beaker with sludge was then inserted in the 105°C oven for 24 hours. The beakers with sludge were thereafter scaled and the weight after oven is the amount of total solids. The difference between the weight before and after oven is the amount of water that the sample contained.

Volatile solids (VS)

To determine the amount of volatile solids in the sludge, the same procedure as for the analysis of TS was used, but with an oven called Wykeham Farrance International 71200/2 and heated to 550°C for four hours instead. The difference between the weight before and after the oven is the amount of water and volatile solids that has evaporated in the oven. Together with the TS result, the unit VS of TS (%) can be determined for the sludge.Two different samples were taken for TS and VS analysis.

2.2.4.2 Nutrients

The nutrients measured were nitrogen, phosphorous, potassium and also the micronutrients Mg, Ca, SO_4, and Na. See methodology for the mentioned elements below:

Nitrogen

Sample preparation: After collection, the sludge was air-dried for five days to let water evaporate from the sample. After drying the samples were crushed with a mortar and sieved to a size of 150 µm. The sieved samples were thereafter stored in sealed bottles in room temperature until the day of analysis.

Analysis S: The total nitrogen was measured as a dry sample of 100 mg in a Vario Max CN from Elementar.

Phosphorous

Sample preparation*:* After collection, the sludge was air-dried for five days to let water evaporate from the sample. After drying the samples were crushed with a mortar and sieved to a particle size of 150µm. The samples were thereafter stored in sealed bottles in room temperature until the day of analysis.

Analysis S: The samples were digested according to Swedish standards SS (0)28311 (1 g dry sample is digested in 10 ml of concentrated HNO_3 and 10 ml H_2O in an autoclave). The phosphorous content was measured with ICP-OES, Optima 8300 from PerkinElmer.

Potassium

Sample preparation*:* The collected samples were first air-dried for five days and thereafter dried in oven ELE International of 105°C for one day. After drying, samples were crushed with a mortar and sieved to a particle size of 150 µm. 0.5 g of each sample were then put in crucibles together with 100 ml of distilled de-ionized water and 12 ml of concentrated HNO_3 in order for digestion to occur. The samples were then heated on heating plates until the volume of the solution was approximately 0.5 ml. Thereafter the samples were air-cooled and then filtered through a Whatman No. 42 filer paper and quantitatively transferred to a calibrated flask and diluted with de-ionized water until 25 ml.

Analysis S: The samples were digested according to Swedish standards (1 g dry sample is digested in 10 ml of concentrated HNO_3 and 10 ml H_2O in an autoclave). The potassium content was measured in ICP-OES, Optima 8300 from PerkinElmer.

Micronutrients

Sample preparation*:* After collection, the sludge was air-dried for five days to let water evaporate from the sample. After drying the samples were crushed with a mortar and sieved to a size of 150µm. The sieved samples were thereafter stored in sealed bottles in room temperature until the day of analysis.

Analysis S: The samples were digested according to Swedish standards (1 g dry sample is digested in 10 ml of concentrated HNO_3 and 10 ml H_2O in an autoclave). The content of micronutrients was then measured in an Ion Chromatograph, Advanced impact IC861 from Metrohm.

2.2.4.3 Heavy metals

Sample preparation*:* The collected samples were first air-dried for five days and thereafter dried in oven ELE International of 105°C for one day. After the drying, samples were crushed with a mortar and sieved to a particle size of 150 µm. 0.5 g of each sample were then put in a crucible together with 100 ml of distilled de-ionized water and 12 ml of concentrated HNO_3 in order to digest the sample. The samples were then heated on heating plates until the volume of the solution was approximately 0.5 ml. Thereafter the samples were air-cooled and then filtered through a Whatman No. 42 filer paper and quantitatively transferred to a calibrated flask and diluted with de-ionized water until 25 ml.

Analysis B: A Micro Plasma spectrometer (Agilent Technologies 4100 MP-AES) was used. The sample solutions were prepared with further dilution as well as the standard needed for the analysis. The dilution factor was one to 100 and was recorded in the apparatus and results were given in ppm.

Analysis S: The samples were digested according to Swedish standards (1 g dry sample is digested in 10 ml of concentrated HNO_3 and 10 ml H_2O in an autoclave). The metal contents were measured in ICP-OES, Optima 8300 from PerkinElmer.

2.3 Result analysis

The result from the laboratory work is discussed and analyzed in the result analysis. The fertilizer potential of the sludge is discussed in terms of legislation, treatment, agriculture demands and in comparison to other sludge types.

3 Area description - Gaborone, Botswana

This chapter will describe Botswana and Gaborone in general terms in order to provide a basic understanding of the use, treatment and management of sludge in the country. Below general facts, water availability and sanitation as well as soil characteristics will be presented, as well as an introduction of the agricultural and industrial sector in Botswana.

3.1 General facts

Botswana is situated in the middle of Southern Africa and has a population of more than 2 million people on a surface area of 582 000 km^2, resulting in one of Africa's lowest population densities. Gaborone is the capital of Botswana and has approximately 300 000 inhabitants (United Nations, 2014; Robinson, 2009). Before the independence in 1966 Botswana was one of the poorest countries in Africa, but since then the country has faced a fast economic growth and is today ranked as a middle-income country (Robinson, 2009). The reason for this fast growing economy is said to be due to rapid urbanization with numerous of industries in e.g. diamond mining, construction, food production, cattle breeding and tourism (Robinson, 2009).

The main challenges for Botswana are increasing water scarcity, high unemployment rate and large spreading of HIV/AIDS (Waves technical report, 2014; Economics Trading, 2015; UNAIDS, 2014). In 2013, approximately 20% of the population was unemployed and around 320 000 people were living with HIV in Botswana (Economics Trading, 2015; UNAIDS, 2014). The water availability and prospects of sanitation are wider described in chapter 3.2.

3.2 Water availability and sanitation

The water resource management is one of Botswana's most critical issues for the future economic growth and development of the country. Botswana is currently facing challenges including droughts, growing water scarcity, water pollution, insufficient sanitation facilities and climate change. The country strives to ensure that water is available in both sufficient volumes and also within an acceptable quality (Waves technical report, 2014).

64% of the total population in Botswana had access to improved sanitation facilities such as flush toilets or pit latrines. This was however not enough to accomplish the Millennium Development Goals 2015 (MDG) target of 75%. The MDG target for improved drinking water sources was exceeded since 97% of the population in Botswana has access to improved drinking water sources (Unicef, 2014).

The average annual water consumption in Botswana in 2011 was almost 200 Mm^3 with 12 Mm^3 used by households (50 l/person and day), see Figure 3.1. The major source of potable water in Botswana is groundwater (49%), water stored in reservoirs from streams and lakes (42%), international rivers (8%) and recycled water (1%) (Waves technical report, 2014).

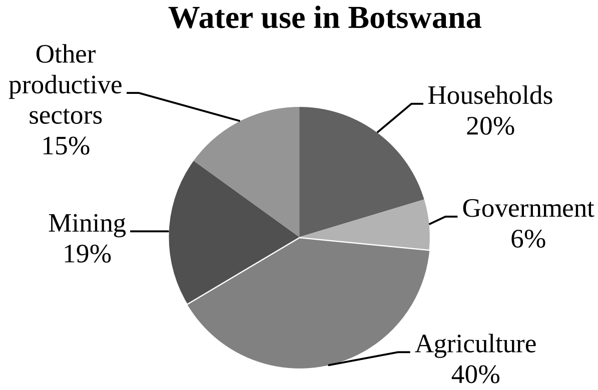


Figure 3.1. Water use in Botswana 2011 (Waves technical report, 2014).

The national water service provider in Botswana is Water Utilities Corporation (WUC). The WUC is owned by the Government of Botswana and is mandated to supply and distribute water, handle water development projects and also engage in regional water sharing agreements with Botswana's neighboring countries, particularly South Africa (Water Utilities Corporation, 2014). Approximately 48% of the drinking water in Botswana is provided by the WUC (Waves technical report, 2014). The Department of Water Affairs (DWA) within the Ministry of Mining, Energy and Water Resources (MMEWR) is in charge of the general planning of water in the country.

The uneven distribution of Botswana's water resources is another large ecological problem. Most of the water sources are situated along the northern border while the population is mainly concentrated in the south, where rainfalls are low and erratic (Fink, 2013). The annual precipitation in Botswana is around 200 mm in the south and 500 mm in the north (Department of Meteorological Services, 2015). Due to the climate change, a decrease of annual precipitation can be expected. The projections by the intergovernmental Panel on Climate Change are that the rainfall will decrease by 30-40% within 65 years and a recent study from Batisani & Yarnal (2010) showed that the climate change is already affecting Botswana.

At the same time as Botswana's water resources are decreasing, a trend of increasing water consumption in Botswana can be seen. The demand is not only increasing due to the highly water-intensive industries (diamond mining, cattle breeding and tourism), but also an increasing number of households connected to the pipe network (Swatuk & Rahm, 2004).

3.3 Soil characteristics in Gaborone

The soil characteristics in Gaborone differ within different locations in the city and the characteristics at a particular location can partially be determined by the underlying bedrock and the influence of anthropogenic factors. It has also been seen that the soil in Botswana contains mainly of minerals containing silicon, iron, aluminum, sodium, calcium and magnesium (Ekosse & Anyangwe, 2012).

In Zhai *et al*. (2003) surface soil samples from urban, agricultural and rural sites in Gaborone were studied in terms of heavy metal content to investigate the impact of anthropogenic activities and bedrock compositions. The results showed that Gaborone urban soils were moderately polluted by lead which was explained as a result of heavy traffic in the city. Soil samples from the agricultural sites showed accumulation of chromium and nickel. This could according to Zhai *et al.* (2003) for example be due to the use of agrochemicals within the agricultural sector. In the residential and industrial soils of Gaborone, zinc was found in moderate concentrations whereas chromium, cobalt, nickel and copper were detected in low levels. Zhai *et al.* (2003) correlated this result to waste disposals within the city. The highest levels of Sc, Cr, Co, Ni and Zn were detected near wastewater treatment plants (Zhai, et al., 2003).

Except from the correlation to anthropogenic sources, Zhai *et al*. (2003) also found a link to the bedrock compositions at different sites. Samples from soil on top of dolerite bedrock showed higher levels of Cr, Ni and Cu than the soil samples from granites and rhyolites. It was seen that this result corresponded to the natural heavy metal concentrations in the mentioned bedrocks (Zhai *et al*., 2003).

3.4 The Agricultural sector

The agricultural sector in Botswana consist of both crop and livestock production. Around 70% of all rural households in Botswana base their living on agriculture, from subsistence farming. The industry dominates mainly by small traditional farms with the average size of around five hectares. This proportion comprises of 63 000 arable farms. Only 110 farms in Botswana are larger than 150 hectares (The United Nations, 2012).

The most commonly produced horticulture crops in Botswana are cabbage, onion, potatoes, tomatoes, butternut and rape. The import of vegetables in Botswana was approximately 40% of the total demand in 2009 (Madisa *et al*., 2012).

During the past 40 years, the agricultural sector in Botswana has experienced a steady reduction in the contribution to national economic growth in Botswana. From a contribution of 43% in the national Gross Domestic Product (GDP) at the independence in 1966, the contribution from the agriculture at 2008 was 2%. The beef industry was in 2008 the only sub-sector of the agriculture that contributed to the GDP (UNDP, 2012).

With the implementation of the National Master Plan for Agriculture and Dairy Development (NAMPAADD), some technical advancement within the agriculture industry has been developed. The result from these investments is still analyzed but a trend can be seen in increasing production for some selected fruits and vegetable crops. In terms of crop production, an increase can be seen especially for tomatoes, cabbage and onions (Ministry of Agriculture, 2002; UNDP, 2012).

The crop production is a very vulnerable part of the agricultural sector since it depends on rainfalls. Small and unpredictable rainfalls lead to varying crop production from one year to the other which makes it a relatively high risk business to be a farmer with low productivity (UNDP, 2012).

3.4.1 Infrastructure and water use in the agricultural sector

In the agricultural sector, there are challenges to meet the demands for irrigation. The main water source for farmers is groundwater from local boreholes but since many of the boreholes in Botswana often have a low capacity, the supply does not meet the demands for irrigation (The World bank, 2009). This leads to more expensive production of crops.

The major challenge for the agricultural sector in Botswana, except from scarcity of water, is thus the lack of infrastructure services. The farms are often situated with long distance apart which is a contributing factor to the difficulties in providing infrastructural services. The National Development plan in Botswana for 2010 showed that a lot of farmers do not have access to roads, electricity and telecommunication. Only 64% of the farmers have water for livestock, 66% have water for domestic use and only 43% have water for irrigation (UNDP, 2012).

3.5 The Industrial sector

The most dominating industries in Gaborone 2005 can be categorized into five main branches: brewery, abattoirs, pharmaceutical, painting and chemical industries (Nkegbe & Koorapetse, 2005). There are also some manufacturing industries for food but many goods are imported from South Africa (Monyamane, 2011). The Water Utilities Corporation is currently working on an investigation of the current industries operating in the Gaborone area that discharges to the sewer system. In March 2015, the total number of industries in Gaborone was documented to around 370 (Motoma, 2015).

4 Impacts and sources of pollutants in wastewater

By knowing the impact of pollutants in wastewater, the characteristics of sludge can be estimated as well as the risks with spreading it on farmland. The sources of these pollutants are also important to know when working with source tracking.

Wastewater contains organic and inorganic compounds of both natural and anthropogenic origin. General streams entering the wastewater system are blackwater (toilet water), greywater (bath/shower/wash water), industrial wastewater and in many cases also stormwater and drainage water. Approximately 99.9% of the total wastewater stream is water whereas the rest consists of dissolved and suspended solids (Gurung, 2014).

Usual constituents of wastewater are nutrients as nitrogen, phosphorous, potassium and sodium, micronutrients, but also hazardous compounds like heavy metals and micropollutants. In too high concentrations, these last mentioned substances can be very harmful for humans and environment. Possible health and environmental risks should therefore be taken into consideration when spreading wastewater-based fertilizers on farmland (Monyamane, 2011; WHO, 2005).

4.1 Organic matter and nutrients

This chapter will describe the characteristics, sources and impacts of organic matter and nutrients (nitrogen, phosphorous and potassium) contained in the wastewater.

Organic matter
Organic matter can be classified into three different categories; carbohydrates, proteins and fats. These compounds consist thereafter of essential nutrients for crop growth. A large part of the organic matter entering the wastewater treatment plant is therefore also available for bacteria to degrade (Hammer & Hammer, 2014). However if the supply of organic matter increases in a water body, eutrophication can occur (Nixon, 1995). This phenomenon leads to a higher consumption of oxygen by living organisms causing oxygen depletion at the bottom of the water body which is not a good environment (Tidlund *et al*., 2015).

Untreated wastewater contains approximately 200 mg/l organic content, which is a parameter that also can be referred as the biochemical oxygen demand (BOD) (Hammer & Hammer, 2014).

Nitrogen (N)
Nitrogen is essential to all living organisms since it is a major element in proteins and nucleic acid. It is therefore also an important element when it comes to plant uptake (Lenntech, 2015; Hammer & Hammer, 2014). The air in the atmosphere consists of 78% nitrogen which is air-bound and therefore not very available for plants and must be bound and converted to readily biodegradable nitrogen like ammonium and nitrate in order to be taken up by plants (National Gardening Association, 1999).

Untreated wastewater consists of inorganic and organic nitrogen with an approximate concentration of 22 and 13 mg/l respectively, based on a wastewater consumption of 450 l per person and day (Hammer & Hammer, 2014).

An overload of pollution-based nitrogen in natural waters could cause eutrophication and algae growth. The ammonia form has also been seen to have toxic effects on fish and is therefore considered as a serious water pollutant (Hammer & Hammer, 2014).

Phosphorus (P)

Phosphorous is an element that is essential for humans, organisms and plants since it is a crucial component in both DNA and RNA. Due to this it contributes to increased plant growth and is essential for the photosynthesis to occur (Elser, 2012; Smil, 2000; Björn, 2014). Phosphorus used for fertilizer is mainly extracted from phosphate rocks (Linderholm, 2011).

Untreated wastewater consists of inorganic and organic phosphorous with an approximate concentration of 4 and 3 mg/l respectively based on a wastewater consumption of 450 liter per person and day (Hammer & Hammer, 2014).

If phosphorous is discharged into a recipient it could lead to eutrophication (Tidlund *et al*., 2015).

Potassium (K)

Potassium is an alkali metal and is most common in the ion form K^+. Potassium is very reactive and is essential for all living organisms (Melander *et al*., 2015). Untreated wastewater consists of approximately 10-30 mg/l potassium (Arienzoa *et al*., 2009). Potassium is not reduced during typical treatment processes and can increase in concentration due to evaporation during the treatment. Since the potassium normally is in the ionic phase, it is dissolved in the water phase and is mainly following the effluent water out from the wastewater treatment plant (Arienzoa *et al*., 2009).

4.2 Micropollutants

Micropollutants are substances with toxic, persistent and bioaccumulative properties that may have negative effect on the environment and living organisms. Pharmaceuticals, pesticides and hydrocarbons are just some examples (Suez Environment, 2013). Micropollutants in the environment are mainly present in very low concentrations, but still they can have a large impact on the ecosystem in the long term perspective. For example can antibiotics harm the microorganism culture in the soil and hormones tend to disturb biological signal pathways (Sundstøl Eriksen *et al*., 2009). Too high concentrations of hydrocarbons can be carcinogenic and reproductive disruptive (Månsson, 2014).

The interest in micropollutants and its hazardous properties for the environment has been raised the last years. Due to better analysis methods it is also easier to observe substances with very low concentrations in the wastewater. This can thus be a reason for the increased interest and many research projects about how substances in very low concentrations can affect the environment during long time exposure (Zupan *et al*., 2013; Choi *et al*., 2012; Boehler *et al*., 2012).

4.2.1 Sources of micropollutants

Pharmaceuticals mainly end up in the wastewater system via the human excreta or by discharge from pharmaceutical-related industries (Choi *et al*., 2012). Some types of pharmaceuticals is removed in wastewater treatment and separated to the sludge, but a large part is kept in the water phase and follows the treated water to receiving waters (Hammer & Hammer, 2014).

Pesticides can enter the sewer system from runoff or seepage from fields or gardens where they are used and can also origin from floor scrubbing water (Schwarzenbach *et al*., 2006).

Hydrocarbons can origin from chemical industries, hygiene products, detergents, pesticides and construction products (Månsson, 2014).

4.3 Heavy metals

Heavy metals are defined as metals that have a density higher than 5 mg/cm^3. In too high concentrations, most heavy metals have negative effects on the environment and can be toxic for animals and plants (Elding, 2015). Some major sources and impacts of the chosen heavy metals studied in this thesis are described down below.

4.3.1 Impacts of heavy metals on environment and human health

As stated above, heavy metals can be toxic for the environment and living organisms in too high concentration. However, the heavy metals copper, chromium (III) and zinc are trace elements for plants and do only become toxic in high levels of exposures. Nickel, chromium (VI) and cadmium on the other hand do not have any essential role for the plant growth and are toxic even at lower concentrations (Tervahautaa *et al*., 2014; Ottaviani *et al*., 1989; Braam & Klapwijk, 1981). Table 4.1 shows examples of impacts caused by high exposure of mentioned heavy metals.

Table 4.1. Examples of health impacts of too high heavy metal exposure

Metal	Impacts
As	Gastrointestinal disorders and lower-limb paralysis can arise[1]
Cd	Injuries on the kidneys, cancer and brittle bone disease[2]
Cr	Toxic in too high concentrations. Cr(VI) is antibacterial and can harm aquatic living organisms[3]
Co	Skin eczema, lung problems like asthma[4]
Cu	Toxic in too high concentrations. Can cause diarrhea and emesis[5]
Pb	Metabolic and neuropsycological disorders, intelegence reduction for children[6]
Ni	Cancer, can inhibit enzyme processes[7]
Zn	Nausea, vomiting, pain, cramps and diarrhea[8]

4.3.2 Sources of heavy metals in wastewater

Heavy metal contents in wastewater origins from both industries and households (Levlin *et al*., 2001). The heavy metal content in domestic wastewater derives from several of sources but a large contributor is the daily used products in the households. The industrial discharge to the sewage system is also a great source for heavy metal in wastewater. Examples of industries contributing to heavy metal discharge are metal manufacturing, mining workshops, tanneries and smelting among others (Kadirvelu *et al*., 2001). Table 4.2 shows some examples of common sources for the heavy metals of interest in this thesis.

[1] Nkegbe (2005)
[2] Elding (2015), Bjellerup *et al*. (2005), Järup & Åkesson (2009)
[3] Elding (2015)
[4] Malmqvist & Elding (2014)
[5] Lundh, *et al*., (2015), Månsson (2014)
[6] Månsson (2014)
[7] Haeger-Aronsen (2015)
[8] Fosmire (1990), Månsson (2014), Nkegbe (2005), Sveder (2002)

Table 4.2. Examples of sources of heavy metals

Metal	Sources
As	Feces and urine, food preservatives, food products, medicine, ore smelting, paints & pigments, pesticides, refining industry[9]
Cd	Alloys, cosmetics & hair care products, feces and urine, pesticides, paints & pigments, stabilization for plastics, tap water, washing powders [10]
Cr	Alloys, cleaning products, feces and urine, fire extinguishers, health supplements, impregnation, paints & pigments, pesticides, photographic, tanneries, tap water [11]
Co	Alloys, Catalysts, food products, food sterilization, health supplements, medicine, overachiever materials like flight engines and turbines, paints & pigments [12]
Cu	Cleaning products, cosmetics and hair care products, electrical equipment, food preservatives, food products, fuels, health supplements, inks, medicine, naturally occurring in the soil, paints & pigments, pesticides, polish, water pipelines[13]
Pb	Cables, batteries, feces and urine, food preservatives, food products, fuels, lubricants, paints & pigments, solder material, tap water, washing powders, [14]
Ni	Constituents in kitchen furniture, cosmetics and hair care products, electrical industries, feces and urine, paints & pigments, pesticides, vehicles[15]
Zn	Batteries, cosmetics and hair care products, feces and urine, food products, fuels, galvanized products, health supplements, lubricants, medicine, polish, paints & pigments, PVC plastics, roofs, Tap water, washing powders, [16]

Besides the above mentioned metals, aluminum (Al) and iron (Fe) are also studied. Aluminum is the third most common element in the earth crust. At a low pH, Al can cause problem for the plants since the nutrient uptake can be inhibited, but it is not bio-accumulating in the food chain (Södergren, 2015). Iron is the fourth most common element in the earth crust and is an essential micro-nutrient for plants (Björn, 2015).

4.3.3 Sources to heavy metals in wastewater in Gaborone

About 25% of the wastewater in Gaborone comes from industries and in March 2015, the WUC had identified 370 industries that were connected to the sewer network (Monyamane, 2011; Motoma, 2015). Most of the heavy metals in the wastewater that goes to GWWTP originate from industrial effluent. Botswana is not a very heavily industrialized country, but still there are potentially sources to heavy metals in the industrial wastewater (Nkegbe, 2005).

The impact of the industrial effluents to the Gaborone sewer system was examined by Nkegbe & Koorapetse (2005) in order to track the sources of four heavy metals in the sludge from GWWTP. Effluent discharge from five of the most dominating industry branches in Gaborone was examined:

[9] Nkegbe (2005), European commission (2011)
[10] Elding (2015) , European commission (2011)
[11] Elding, *et al.*, (2015) , European commission (2011)
[12] Öwall & Elding (2014) , European commission (2011)
[13] Lundh, *et al.*, (2015), Månsson (2014) , European commission (2011)
[14] Nkegbe (2015), Månsson (2014) , European commission (2011)
[15] Haeger-Aronsen, *et al.* (2015), Nkegbe (2005) , European commission (2011)
[16] Fosmire (1990), Månsson (2014), Nkegbe (2005), Sveder (2002) , European commission (2011)

brewery, abbatory, pharmaceutical, painting and chemical industries. The result showed that none of the mentioned industries discharged Cd, Pb or Zn, but all of the studied industries discharged Ni and the painting industry discharged the most.

5 Wastewater treatment

A conventional wastewater treatment plant consists of several different steps that all contribute to treat the wastewater to acceptable levels for discharge into a recipient. Commonly found treatment steps on a conventional wastewater treatment plant are: initial treatment, primary treatment, secondary treatment and tertiary treatment. There is often also some form of sludge treatment at or in connection to the plant. Each step functions differently and contributes in various ways to the treatment of the wastewater (Oliver & Cosgrove, 1974; Stoveland *et al*., 1978; Lester, *et al*., 1979).

Treatment steps for both wastewater and sludge are described below, focusing on the treatment processes used at Glen Valley wastewater treatment plant.

5.1 Initial treatment

The incoming wastewater to the treatment plant first enters an initial treatment step, which focus on removing large and undesired particles that can obstruct the continued treatment processes. The wastewater flows through a coarse screen where larger particles like rags and garbage are removed to a great extent (EPA, 2003). Thereafter the wastewater is led through an aerated grit chamber for removal of sand and soil particles (Hammer & Hammer, 2014).

5.2 Primary treatment

After the initial treatment, the wastewater flows further to the primary treatment step. In the primary settling tank heavy and solid particles settles to the bottom and oil and grease will float on top and then be separated from the liquid stream (Lidström, 2013; Hammer & Hammer, 2014). The separated materials are brought together and are hereby called primary sludge. The sludge is thereafter further transported to the sludge treatment plant, see chapter 5.5. (Hammer & Hammer, 2014; Wang *et al*., 2006). Approximately 50-70% of the total suspended solids and 65% of the oil and grease are commonly removed during the primary treatment (Pescod, 1992).

Below, the removal of nutrients, organic matter and heavy metals associated with the primary treatment will be described more detailed.

5.2.1 Nutrient and organic matter removal

Only a small fraction of nutrients are removed in the primary treatment. This is mostly organic forms of nitrogen and phosphorus. Dissolved and colloidal matters are not affected to a great extent (Pescod, 1992). The amount of nutrients removed in the primary treatment step can be estimated to 15% for nitrogen and 15% for phosphorus (Hammer & Hammer, 2014).

Approximately 25-50% of the incoming organic matter (BOD) is removed in the primary treatment step. This part can both consist of heavier organic solids that settles to the bottom of the basin, or lighter organic materials that float on the top (Pescod, 1992).

5.2.2 Heavy metal removal

Heavy metal removal in the primary treatment step occurs mainly for those metals that are adsorbed to particles or that appears in insoluble form. These forms of heavy metals tend to sink to the bottom of the settling tank and can therefore be separated from the wastewater to the primary sludge (Oliver & Cosgrove, 1974; Barth *et al*., 1965; Stoveland *et al*., 1978). Approximately 70% of the total content of cadmium, chromium, copper, lead and zinc are removed in the primary treatment according to Stoveland *et al* (1978).

The removal of heavy metals in the primary treatment step depends on influent wastewater concentrations. The concentration can vary at different location, but also from one time to another at the same treatment plant (Lester, 1983). Since the content of heavy metals in the primary sludge reflects the quality of the incoming wastewater, heavy metal analysis of the primary sludge can give an idea of which and what form of heavy metals that settles during the treatment that can be found in the wastewater.

According to a study at Gaobeidian wastewater treatment plant in China, the concentration of seven of eight analyzed heavy metals were higher in the primary sludge than in the secondary sludge (Wang *et al*., 2006).

5.3 Secondary treatment

After the primary treatment, the wastewater is transported to the secondary treatment where the wastewater in most cases is treated biologically with microorganisms (Naturvårdsverket, 2008). There are different processes that can be used for secondary treatment but the most used is the activated sludge process, which has been used for over 100 years (Aqua Enviro, 2012). The activated sludge process will therefore be prioritized in this section.

The activated sludge process basically aims at optimizing the natural mechanism of microbial degradation of organic matter. Microorganisms that are present in the activated sludge process can with the supply of oxygen consume organic matter and nutrients while carbon dioxide is produced. Firstly cell growth is favored by the continuous supply of organic materials and oxygen and then in the secondary settling tank the microorganisms are allowed to flocculate and settle to the bottom of the basin. The solid fraction is then separated and is hereafter called secondary sludge, containing different types of microorganisms mainly containing organic matter, nitrogen and phosphorous (Hammer & Hammer, 2014; Nesc, 2003).

In order to have an efficient and stable treatment process, a part of the secondary sludge is returned to the activated sludge basin. By returning the sludge, a desired equilibrium is obtained between the free-swimming and the flocculating microorganisms, which is an important factor for the sludge production (Nesc, 2003). This optimal sludge age (the time that the sludge is in the activated sludge process) can be calculated in order to achieve the desired and optimal composition of different types of microorganisms (Stockholm vatten, 2015).

5.3.1 Organic matter and nutrient removal

The organic matter and nutrient removal is described in three sections; organic matter, nitrogen and phosphorous.

Organic matter

At the secondary treatment step the organic matter content in the wastewater dominates in the dissolved form. This is the case since most of the insoluble forms have already been extracted in the primary treatment step. Up to 80% of the organic matter (BOD) can be removed in the activated sludge process (Hammer & Hammer, 2014).

Nitrogen removal

By letting wastewater pass through both aerated (oxygen supply) and anoxic zones (no oxygen supply but NO_x is present) different forms of nitrogen can be treated. Due to the presence of oxygen in the aerobic zones the nitrification process can occur, where nitrifying bacteria convert ammonia (NH_4^+) to nitrite (NO_2^-) and then nitrate (NO_3^-) Nitrate is removed in anoxic zones where the denitrifying bacteria convert it to nitrogen gas (N_2) that goes to the atmosphere (Stockholm vatten, 2015). But regardless of treatment process in the secondary treatment step, nitrogen is mainly removed using intermittent aeration. The nitrogen removal depends on the process and wastewater characteristics, but approximately 20% nitrogen can be removed if no anoxic zones for denitrification occur (Naturvårdsverket, 2008).

Phosphorous removal

With the natural conventional activated sludge process, approximately 20% phosphorous can be removed, (Naturvårdsverket, 2008). In order to increase the phosphorous removal to the sludge, enhanced biological phosphorous removal can be used. This method is described below.

Enhanced biological phosphorous removal means that the wastewater is subjected to alternating anaerobic and aerobic conditions in order to stimulate excessive storage of phosphorous for specific bacteria (Bio-P bacteria). These bacteria occur naturally in the wastewater meaning that the biological phosphorous removal can be done within the activated sludge process, but are not that common at the moment. In anaerobic conditions, the bio-P bacteria use the stored energy from the polyphosphate chains to assimilate volatile fatty acids (VFA) in the wastewater. The same time as VFA is taken up, phosphorous is released from the microorganisms meaning that the content of phosphorous increases in the wastewater stream. The VFA is stored as polyhydroxyalkanoates (PHA) in the microbial cell. When the environment then shifts to aerobic conditions the bio-P bacteria will be able to consume stored PHA in order to assimilate phosphate ions from the wastewater for internal storage. The bio-P bacteria take up more phosphate ions in the aerobic zone than what they release in the anaerobic zone, resulting in a net-uptake of phosphorous. Phosphorous stored in the bacteria can hereafter leave the system with the secondary sludge. The separation of the sludge occurs most often in a sedimentation basin after the aerobic zone, the stage where the bio-P bacteria have just filled up the phosphorous storage (Dagerskog, 2002).

5.3.2 Heavy metal removal

The microbial activity is crucial for the removal of heavy metals in the secondary treatment and the activated sludge process. An important mechanism in the removal of heavy metals in the secondary treatment step is bio-sorption, which occurs when heavy metals binds to living cells, biomass or microbial extracellular polymers present in the wastewater (Volesky & Holan, 1995; Oliver & Cosgrove, 1974). Bio-sorption happens for metals in soluble form, and it is mainly these forms of heavy metals that are removed in the secondary treatment step (Oliver & Cosgrove, 1974).

Except from the microbial activity, the removal of heavy metals in this step is also dependent on the composition of the wastewater, metal concentration, dissolved organic matter content, available biomass, pH, temperature and retention time of the sludge in the activated sludge reactor (Macaskie *et al*., 1987; Cheng *et al*., 1975; Brown & Lester, 1979; Wang *et al*., 1999). The uptake of metals increases with increasing pH until a pH-value where metals can precipitate as hydroxide (Cheng *et al*., 1975). According to Stoveland *et al*. (1978) it was seen that the sludge age influenced the removal of heavy metals. Heavy metal removal rates were higher in activated sludge processes with higher sludge ages, particularly for lead and zinc. Barth *et al*. (1965) found that the removal rate of copper, zinc, nickel and chromium was dependent on the concentration of dissolved oxygen. It was also found that lead could be removed more efficiently in the secondary treatment step than in the primary treatment since the settling time is much longer in the secondary settler than in the primary.

5.4 Tertiary treatment

Tertiary treatment is often needed to reduce the content of contaminants so that the effluent from the wastewater treatment plants meets the requirements for discharging in receiving water. The tertiary treatment can either serve as an extension of the secondary treatment or focus more on advanced treatment of other contaminants. Some common methods are described briefly below.

Chemical precipitation

In the tertiary treatment, phosphorous can be removed from the wastewater by chemical precipitation with chemical reagents like aluminum sulphate, ferric chloride or lime. The reagents/polymers react with organic matter and nutrients in the wastewater and together from a solid precipitate that can be separated. The process is common to use for phosphorous removal. The main disadvantages with chemical precipitation are the cost of the polymers as well as the fact that they can contain heavy metals which eventually contributes to increased metal content in the sludge (EPA, 2000; Länsstyrelsen, 2002).There are also a scientific discussion about how well the phosphorous from chemical precipitation can be available for plants if the sludge is spread on farmlands, since the chemicals affect the form of the nutrients (Linderholm, 2011).

Nature-imitating treatment

By using constructions like sand filters, lagoons, maturation ponds and wetlands, excessive nutrients and substances in the wastewater can be removed by plant uptake and infiltration processes. The constructions can be designed in a way that it favors the removal of nutrients in terms of retention time, aeration, temperature etc. (EPA, 2002).

Disinfection

There are two main methods for disinfection of wastewater: ultraviolet radiation and chlorination. When ultraviolet radiation is used, the DNA of the bacteria cell is broken down and it becomes incapable of reproduction. The UV-lights must be kept from fouling and be replaced on a regular basis for continued and effective disinfection. The effluent wastewater can also be disinfected by using chlorine. The risk of using chlorine is that it in combination with any organic material can form organochloride-compounds which are toxic for the aquatic environment. This can though be avoided if the wastewater after chlorination is exposed to for example activated carbon or sulphuroxides (EPA, 2002).

5.5 Sludge treatment

For economic, spatial and hygienic reasons, the sludge from a wastewater treatment plant must be further treated after it has been separated in the WWTP. The main purpose of the sludge treatment processes is to produce a stabilized and hygienized product, reduce the volume and to remove water. If this is done, problems with smell and handling can be eradicated (Sanin *et al.*, 2011; Nilsson & Dahlström, 2005).

There are several different methods used for sludge treatment, like conditioning, thickening, dewatering, stabilization and hygienization. These processes are briefly described below.

<u>Sludge conditioning</u>
The sludge conditioning aims to improve the properties of the sludge to make further sludge treatment more effective. The conditioning can be done chemically where mineral agents like lime, salts or organic compounds are added to the sludge or it can be done thermally. This is done to get the best properties (such as moisture content and pH) of the sludge before it will be further treated (European Commission, 2001b).

<u>Sludge thickening</u>
Sludge thickening is done in order to reduce the volume of the sludge and make it easier to maintain in further treatment steps. If this is done, the costs for the following treatments will also be reduced. The sludge can be thickened with different methods depending on the sludge characteristics and the purpose of the treatment. Flotation, sedimentation and centrifugation are just some examples of thickening methods (European Commission, 2001b).

<u>Sludge stabilization - Anaerobic digestion</u>
With an anaerobic digestion process, sludge is digested anaerobically with no presence of oxygen. In this process carbohydrates, fats and proteins are broken down while methane gas and carbon dioxide are produced. Benefits with using anaerobic digestion are that the total volume of the sludge can be reduced by about 35%, pathogen content is reduced and that the methane gas is an energy source (Nilsson & Dahlström, 2005; European Commission, 2001b).

<u>Sludge stabilization – Aerobic digestion</u>
In the aerobic digestion process, the sludge is digested with presence of oxygen. The process aims to digest organic matter which generates heat. Aerobic digestion is not that common since it usually is expensive in comparison to the prize you can sell the product for (Sanin *et al.*, 2011). If addition of vegetal co-products is done during the composting process, a more stable product is presented. Sludge treated with aerobic digestion is considered as nutrient-poor in terms as fertilizer (European Commission, 2002).

<u>Sludge stabilization – Lime</u>
A way to stabilize sludge is to raise the pH to above 11,12 so that no biological activity can occur. This can be done using lime in the forms called quick lime (CaO) or hydrated lime ($Ca(OH)_2$). Lime is considered to be a safe alternative since no unwanted by-products are produced (Sanin, et al., 2011). But the costs for lime might be high since around 30% of the dry solid content has to be added to reach the desired pH (European Commission, 2001b).

Sludge dewatering

The dewatering process focuses on reducing the volume of the sludge mass by separating water from the sludge and therefore reducing the water content. The process can for example consist of a plate press, belt press, centrifuge or drying bed (Fytili & Zabaniotou, 2008).

Sludge hygienization- Solar UV-radiation

For additional disinfection of pathogens, UV-radiation, sunlight or increase in temperature are all factors that contribute to increased disinfection rates. How effective the hygienization is depends highly on the climate and it can take up to one month to eradicate the pathogens in the northern hemisphere (European Commission, 2001b; Nicholson *et al*., 2005). According to REVAQ rules in Sweden, the sludge should be stored 6 months before it is used-just in case (REVAQ, 2014).

6 Wastewater and sludge treatment in Gaborone

This chapter will describe the management and treatment system of wastewater and sludge in Gaborone, starting with the sewer network and thereafter a description of the wastewater and sludge treatment at the treatment plant.

Glen Valley wastewater treatment plant receives wastewater from Gaborone City and the surrounding areas. The plant has recently expanded to handle an increasing load of wastewater from Gaborone city and the capacity has increased from 40 ML/day to 90 ML/day if both the old and the new plant are in use. The amount of PE connected was not known (Garekwe, 2015). The information in this chapter was found at visits at the plant with descriptions from Garekwe (2015).

6.1 The sewer network

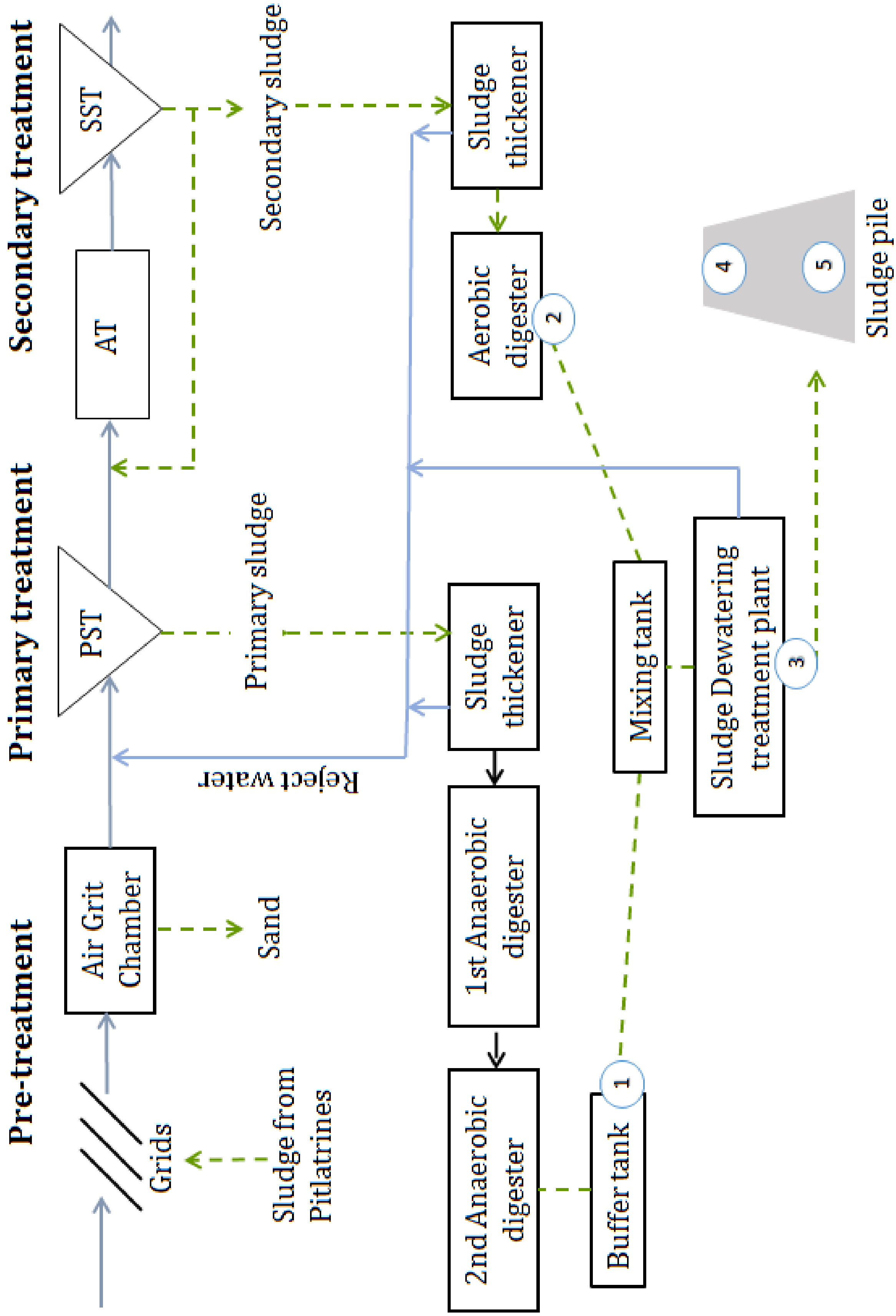
The sewer network in Gaborone transport wastewater from domestic and industrial sources to the wastewater treatment plant in Glen Valley. The stormwater is transported in a separated system and is directly discharged to the receiving water bodies without passing the treatment plant. It is currently not clear how many people that are connected to the sewer system today but an investigation by WUC is proceeded to locate the number of PE (person equivalents) connected (Sagothusi, 2015).

The wastewater pipes are made out of materials like PCB, clay and asbestos cement. The Water Utilities Corporation is experiencing challenges with blocking in pipes due to fat and grease and garbage. It is common that manhole lids are stolen and branches and garbage enter the sewer network (Sagothusi, 2015).

6.2 Wastewater treatment at GWWTP

The treatment plant consists of facilities for primary treatment, secondary treatment with an activated sludge process, sludge treatment and finally effluent water treatment with maturation ponds, see Figure 6.1. The effluent from the plant is released to maturation ponds and then discharged to the Notwane River. The operators at the plant are experiencing some maintenance challenges in the processes, such as sand in the wastewater, leaking of wastewater and too small budget. Below the different steps are described in more details. The targets for wastewater treatment are also described in this chapter.

Figure 6.1. Process scheme of Glen Valley wastewater treatment plant.



6.2.1 Pretreatment

When wastewater together with an external supply of fecal sludge from pit latrines enters the Glen Valley wastewater treatment plant, it first passes a pretreatment step. In this step, the wastewater is firstly screened by coarse and fine grids in order to remove larger particles and foreign materials. The wastewater is thereafter treated in an aerated grit chamber for removal of residual coarse objects, especially sand or particles with similar size and densities, which can disturb the further treatment processes. Unfortunately there are some problems with the air grit chamber at the moment and sand is following the wastewater to the other treatment steps.

6.2.2 Primary treatment

After the pretreatment the wastewater is further transported to the primary treatment in the primary settling tanks. The produced primary sludge is separated and thereafter transported to the sludge treatment process at the plant. Here, the primary sludge consists of 98% water (Garekwe, 2015).

6.2.3 Secondary treatment

The effluent water from the primary treatment is transported to the secondary treatment which includes an activated sludge process. In this step, the wastewater first enters a small anoxic zone before it enters the aerated zone. Thereafter the wastewater is transported to a secondary settling tank. From the secondary settling tank sludge is separated and a fraction is transferred back to the anoxic zone in the activated sludge process. The non-recirculated sludge from the secondary settling tank is pumped to the sludge treatment processes. The effluent water from the secondary settling tank is then entering two areas of maturation ponds where polishing of the effluent is taking place including kill off of pathogens due to UV light from the sun introduced in the shallow ponds. The effluent from the maturation ponds are then released in the Notwane River.

6.2.4 Targets for wastewater treatment

In order to control and analyze the treatment processes and efficiency of the treatment plant but also the quality of inflow to the plant, the WUC has set up regulations for wastewater characteristics. The regulations describe the maximum limits for quality of the incoming wastewater but also for the effluent water from the treatment plant after treatment, see Table 6.1.

Table 6.1 Maximum limits for wastewater entering and leaving GWWTP

Parameter (mg/l)	Raw wastewater (maximum levels)	Effluent water (Maximum levels)
P	30	1.5
NO_3^--N	100	10
NH_4^+-N	200	50
Na	500	400
SO_4^{2+}	1000	400
As	5	0.1
Cd	5	0.02
Cr (total)	10	0.5
Cu	5	1
Fe	20	2
Pb	5	0.05

6.3 Sludge treatment at GWWTP

The sludge produced after the wastewater treatment is further treated in a sludge treatment process at Glen Valley treatment site. This sludge treatment plant was built in 2009/2010, replacing an old plant. The annual sludge production from Glen valley wastewater treatment plant is not documented but is estimated to approximately 600-800 m^3 according to Madilola (2015) and approximately 4000 m^3 according to Centre for Applied Research (2013). It has been seen that the sludge production has increased in Botswana and especially in Gaborone during the past years. The reasons could be rapid population growth and introduction of advanced wastewater treatment techniques (Ngole *et al.* 2006).

Sludge from GWWTP is formed in both the primary and secondary treatment processes (primary and secondary sludge) where the both types of sludge are treated separately in different sludge thickening tanks. In the thickening tanks the water content in the sludge is reduced from approximately 98% to 94%. The primary sludge is then treated anaerobically in anaerobic sludge digester tanks whereas the secondary sludge is instead treated aerobically in aerobic digester tanks. After the different digestions, all the sludge is mixed and further pumped to the dewatering plant. In this process sludge is mixed with a polymer and water is pressed out in filter presses. Approximately 80 - 85% of the water can be removed in this step.

In all the sludge treatment steps the supernatant effluent is reversed to the inlet of the primary settling tank. The final sludge is transported with trucks around 300 meters to be stored at the end of the plant site. Here it is stored in piles where it can dry even more.

Before the new sludge treatment plant was built in 2009/2010, sludge was instead dried in drying beds on the site. The sludge drying beds also includes a system that takes care of excess water from the sludge and is built in squares where one pile is stored in every square.

7 Sludge management and fate

This chapter focuses on the sludge management and fate of sludge after the treatment processes. The sludge management in Gaborone is compared with the system in Sweden and the fate of sludge in Botswana is related to applications for sludge in both Sweden and the European Union.

7.1 Sludge management

An important factor for the availability and possibility of using sludge as fertilizer is the commercialization and management of the sludge and thereby fertilizer product. The sludge management can cost up to 50% of the wastewater treatment total costs and is therefore of economic importance for the treatment plant. However, to get a reliable product that people want to buy, focus must be put on the handling after the sludge treatment. It is often therefore important to have open information, products that can be traced and information campaigns. The public opinion about the use of sludge is an important factor if the sludge should be sold which makes it important for the producer to take certain care of the public view and trust (Campbell, 2000).

This chapter will introduce sludge management that in this context means everything from the sludge treatment to the customer´s use in Gaborone and Sweden.

7.1.1 Sludge management in Gaborone

There is a current plan for the management of sludge from Glen Valley wastewater treatment plant but since the plant is relatively newly built, it has not been prioritized yet.

After the treatment, sludge is stored in piles at the site where people can come and load their truck. The sludge can be collected from anywhere at the sludge piles and in order to keep track on the sold amount of sludge, the loaded vehicles are weighed on the way out from the plant. The sludge from GWWTP is sold for 5 BWP/ton (approximately €0.5/ton) (Madilola, 2015).

There is no campaigning to the public informing that the sludge can be bought from the treatment plant and it is therefore mostly people and farmers from around the plant that knows about it (Monametsi, 2015).

At the moment there is no found legislation for spreading of sludge on agricultural fields but there is an investigation going on to implement regulations (Madilola, 2015; Monametsi, 2015; Odirile, 2015).

7.1.2 Sludge management in Sweden

Sludge management has been discussed in Sweden for several decades and a certification system called REVAQ has developed. Wastewater treatment plants can voluntarily choose to be certified by REVAQ and follow a number of rules in order to produce and sell totally traceable sludge. That means that the amount of sludge, the production period and the time for delivering and spreading on agricultural fields need to be official and registered in a map database that the Swedish water association Svenskt Vatten provides (REVAQ, 2014). REVAQ also handle the system of source tracking in Sweden, which will be discussed in chapter 8.2.

The sludge that is spread on farmland has a product sheet that describes the name of the treatment plant, certification number, the actual sludge batch number, sludge production time, amount, treatment of the sludge, the storage of the sludge and a contact person at the treatment plant. It should also contain the amount of total-P, total-N and ammonium-N. The sheet should also contain the metal concentrations of Pb, Ni, Cu, Cr, Zn, Cd and Hg in mg/kg TS and g/ha and year (REVAQ, 2014).

At certified plants the sludge should always be stored in batches. Before the sludge batch can be used in agriculture, documentation of the production time, amount, analysis, calculated amount of phosphorous that will be spread on the field, salmonella analysis and the product sheet are needed. There should also be documentation about the actual field (if it has got sludge before, metal content in soil etc.) and the agreement between the farmer, sub supplier and the plant. The spreading should then proceed after a documented routine and a summary of all the information about the spreading that should be available for the inspection authority or agricultural companies (REVAQ, 2014).

The wastewater treatment plants that are not REVAQ-certified or have disapproved REVAQ-sludge are not very accepted to spread on farmland. Then it is mainly used as filling material in landfills or constructions (Naturvårdsverket, 2012a).

7.2 Fate of sludge

One of the hardest and most expensive challenges in wastewater engineering has for a long time been to find the ultimate utilization for the sludge (Korentajer, 1991). Common fates of the wastewater sludge can be fertilization, landfill disposal and incineration but also sea disposal (European Commission, 2002; Campbell, 2000). Both landfill disposal and incineration of sludge can cope with an isolation of hazardous material, but the strategies are expensive and can cause problem in the environment if it is not proper maintained. It does not recycle the nutrients in the sludge and requires energy, meaning that sustainable development is hard to achieve with these methods (García-Delgado *et al*., 2007; Tervahautaa *et al*., 2014).

7.2.1 Fate of sludge in Gaborone

The information about sludge application and the use of sludge in Botswana is limited. There are only two fates of the sludge in Gaborone; sludge is either sold to farmers and individuals for fertilizing purposes or continually stored at the treatment site.

7.2.2 Fate of sludge in Sweden and EU

There is an on-going discussion in Sweden about the fertilizer use of sludge. The acceptance of using sludge as fertilizer due to the sometimes high content of hazardous compounds is the main challenge. Disposal of organic waste is forbidden in Sweden and therefore the sludge is not put on landfills. However a relatively large amount are just stored, see Figure 7.1. In EU there is generally also a problem with the acceptance of using sludge as fertilizers. Therefore a lot of sludge is disposed on landfills today, see Figure 7.2 (Fytili & Zabaniotou, 2008).

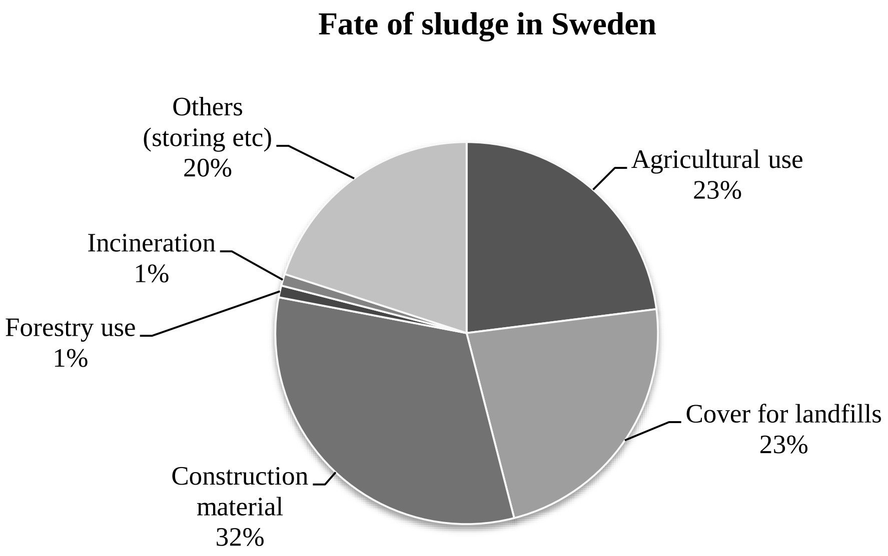


Figure 7.1. Fate of sludge in Sweden (Naturvårdsverket, 2012a; Statistiska Centralbyrån, 2014a)

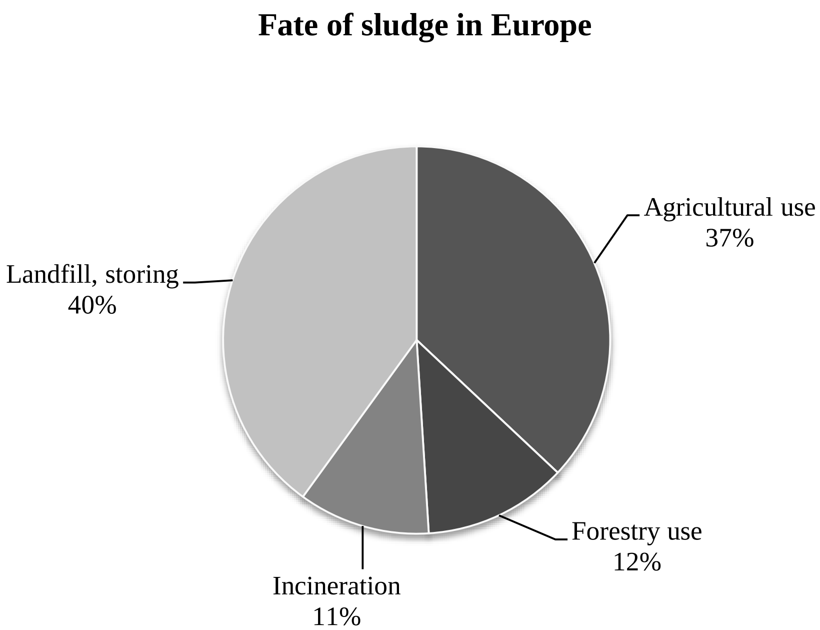


Figure 7.2. Fate of sludge in Europe (Fytili & Zabaniotou, 2008)

8 Fertilizers

The use of fertilizers in agriculture has for a long time improved the life situation for many people all over the world due to the consequence of increased crop growth. But as the population increases, the demand for fertilizers will also be greater (Cordell *et al*., 2011). It was estimated in 2011 that without the input of nutrients from fertilization, only half of the world's population could get enough food for living (Dawson & Hilton, 2011).

Fertilizers are used in order to supply the soil with nutrients in order to favor plant growth. This extra input of nutrients is especially needed at fields where crops and plants are harvested due to the fact that nutrients are lost when crops are removed from the soil. If the plant was degraded instead, the natural supply and recycling of nutrients to the soil would occur (Henriksson, et al., 2012). Even if crops are efficiently cultivated with high productivity, fertilizers are often needed in order to avoid depletion of the soil. Furthermore a large portion of the soil in the world would not be fertile enough for crop production if not fertilizers were added (Dawson & Hilton, 2011; Erisman *et al*., 2008; Elser, 2012).

The use of fertilizers in agricultural does also have drawbacks. If fertilizers are applied beyond the growing season, some of the nutrients will be lost and thus polluting nearby recipients. This is the case since there will be no plants available to take up or immobilize the nutrients during this season. It is therefore also a great risk that nutrients from fertilizers will end up in groundwater or receiving water bodies causing pollution and eutrophication if they are not used properly (Lenntech, 2015).

This chapter will continue by focusing on the fertilizer requirements but also on different types of fertilizers present on the market today.

8.1 Fertilizer requirements

There are several requirements for the use of fertilizers in agriculture. A fertilizer should have a high nutrient value and have nutrients in accessible form for plant uptake, but it should also improve the soil structure and be easy to handle. In addition to this, a fertilizer should not contain any hazardous substances (National Gardening Association, 1999). These demands and requirements are described more in detail below.

8.1.1 Nutrient value

Except from sunlight, water and carbon dioxide, the availability of nutrients and minerals in the soil is essential for plant growth (National Gardening Association, 1999). The most important nutrients for a plant to grow are the macronutrients nitrogen (N), phosphorus (P) and potassium (K). Other nutrients needed are calcium (Ca), sulphur (SO_4), sodium (Na) and magnesium (Mg) as well as micronutrients like boron (Bo), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn). These lastly mentioned nutrients are essential but only required in very small quantities (Ljung *et al*., 2013; Petersson, 2008).

Nutrients are available in both organic and inorganic form but it is the inorganic form that is available for plant uptake. For nitrogen, there are three major inorganic forms: nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+). Of these forms of inorganic nitrogen, nitrate is often most preferable since there is a risk that ammonium can be lost in transformation into gaseous ammonia (NH_3) when exposed in the open air (Ljung *et al*., 2013). The organic nutrients must be mineralized before it can be taken up by the plants (Petersson, 2008).

8.1.2 Heavy metal content

Plants are not only able to assimilate nutrients but also heavy metals from the soil. It is therefore important to regulate and control the heavy metal content in fertilizers so that it won't cause harm to the environment or human health.

There are several factors influencing the metal uptake by crops; concentration of metals in the soil, pH, organic matter content, crop type and crop age are just some important parameters. According to Jung & Thornton (1996) the most affecting factor for the plant uptake of heavy metals is the concentration of metals in the soil together with the pH. With low pH-value in the soil, the metal uptake is high, and if the concentration of metals in the soil is high, the plant uptake of metals will also be high (Jung & Thornton, 1996).

Additionally the configuration of the plant is of importance for the heavy metal uptake. The leafy part of the crop seems to accumulate higher concentrations of metals than roots, grains or fruits (Jung & Thornton, 1996).

In order to measure the supply of heavy metals when fertilizing, the heavy metal content in fertilizers is often presented in comparison with the content of nutrient (mg metal/kg nutrient). The reason why this unit is chosen is that differences in heavy metal input by different fertilizer alternatives and sludge types will be clearer if it is presented in relation to the supply of nutrients.

8.1.3 Soil structure and maintenance

Except from the nutrient value, there are also requirements that the fertilizer product should be stable and homogenized as well as easy to maintain. A fertilizer should be composed by either solid granules or be in liquid form so that it easily can be handled with the machines that most farmers use for fertilizing today. The price of the fertilizer is of course also an important factor (Levlin, et al., 2014; Ljung *et al*., 2013).

8.2 Types of fertilizers

There are many different types of fertilizers used in agriculture; artificial fertilizers, animal manure, digestate from biogas production and wastewater sludge are some of the most frequently used fertilizers on the market today. These are described more in detail below.

8.2.1 Artificial fertilizers

An artificial fertilizer is a synthetically produced product which consists of inorganic minerals and nutrients extracted from the nature in order to nourish and meet the requirements of specific crops (Levlin *et al*., 2014). See example of composition in Table 8.1.

Table 8.1. Nutrient content of artificial fertilizers (Yara, 2015).

Parameter	Artificial fertilizer Yara Mila 21-4-7 (g/kg TS)	Artificial fertilizer Yara Mila 27-2-3 (g/kg TS)
Tot-P	36	20
Tot-N	210	270
NH_4-N	130	150
NO_3^--N	79	120
K	66	30
Mg	9	0
S	30	25

The artificial fertilizer is produced synthetically and nutrients within the fertilizer are extracted from natural resources. Phosphorous and potassium are mainly extracted from rocks whereas nitrogen mainly originates from nitrogen gas extraction from the air, with the input of energy and water (The Fertilizer Institute, 2002; Levlin *et al*., 2014; Socolow, 1999).

The recovery of phosphorus is today mainly made from sedimentary and volcanic rocks and approximately 90% of the world's resources of phosphorus can be found in the first mentioned (Linderholm, 2011; Finnson, 2013). It is estimated that this source of phosphorus from sedimentary rocks will not last longer than around 50-100 years more (Cordell, 2014).

The phosphate rocks do also contain heavy metals to some extent and it is therefore a risk that heavy metals and other hazardous substances follow the nutrient extraction. Cadmium is one example of a heavy metal that can be found in the rocks where phosphorus is extracted. The cadmium content in sedimentary rocks is around 100 mg Cd/kg P and approximately ten times lower in volcanic rocks (Finnson, 2013). There is however techniques for treating the extracted phosphorus fraction from cadmium but this contribute to an increased price of the final product (Elser, 2012). An example of heavy metal content in artificial fertilizers is presented in Table 8.2 (Remy & Ruhland, 2006).

Table 8.2. Mean concentrations of heavy metals for artificial fertilizers, related to nutrients (Remy & Ruhland, 2006)

Element	N-fertilizer as N (mg/kg N)	P-fertilizer as P_2O_5 (mg/kg P)	K-fertilizer as K_2O (mg/kg K)
As	9.3	15	0.1
Cd	6	40	0.2
Cr	78	540	5.8
Cu	26	91	4.8
Ni	21	88	2.5
Hg	0.1	0.3	0.1
Pb	55	67	0.8
Zn	200	840	6.2

8.2.2 Manure and digestate

Animal manure or digestate from biogas production is another possible fertilizer alternative since it contains macronutrients like nitrogen, phosphorous and potassium but also micronutrients and organic matter. The nutrient content in the manure can however vary depending on animal, feeding, bedding material, other supplements but also treatment and management of the manure. Manure can consist of both urine and/or feces from animals like cows, pigs and chickens. (Jordbruksverket, 2015).

Digestate is the solid by-product from biogas plants that is left after the biogas production. This product is rich in nutrients and is therefore also a suitable alternative for fertilization purposes (Al Seadi & Lukehurst, 2012)

An example of nutrient value in cow manure and co-digestate (mixture of digesting-substrates) is shown in Table 8.3. The co-digestate is sampled from 10 different co-digesting plants during 2009 and has a TS value of 3.3% and a mixture consisting of 13% domestic waste, 24% manure fertilizer, 15% waste from food production, 30% abattoirs and 18% other (Ljung *et al.*, 2013). The cow manure has a TS value of 16.6% (Steineck *et al.*, 1999).

Table 8.3. Nutrient value from cattle manure and from co-digestate sampled from 10 different co-digesting plants in Sweden during 2009 (Steineck et al., 1999; Ljung et al., 2013)

Parameter	Co-digestate (g/kg TS)	Cow manure (g/kg TS)
Tot-P	16	9
Tot-N	150	30
NH_4-N	93	13
K	46	28
S	n.m.	5
Na	n.m.	2.6
Mg	n.m.	5.9

n.m. means not measured.

The heavy metal content in manure is very different at different places, but to illustrate what it can be, Table 8.4 shows the heavy metal content in cow manure. However the heavy metal content in manure might be very different dependent on animal and feeding.

Table 8.4. Metal value according to phosphorus and TS from cattle manure (Steineck et al., 1999; Ljung et al., 2013)

Element	Cow manure (mg/kg P)	Cow manure (mg/kg TS)
As	Not detected	n.m
Cd	30	0.16
Cr	1200	2.8
Cu	14000	31
Ni	1500	3.0
Pb	700	0.69
Zn	26000	170

n.m. means not measured.

8.2.3 Blackwater

Black water is the sewage stream originating from the toilet waste; urine, feces and toilet paper. This stream commonly contains a higher nutrient value but less water and hazardous compounds than other wastewater streams entering the wastewater treatment plant. For this reason, blackwater might be a good alternative for fertilizer use (Tervahautaa *et al*., 2014). See Figure 8.1 and Table 8.5 for nutrient value in blackwater and Table 8.6 for general heavy metal content in blackwater, urine, feces and greywater (Frankki & Sternbeck, 2013).

The percentage nutrient content in greywater, feces and urine can be seen in Figure 8.1. According to the figure, blackwater stands for 92% of the total nitrogen content in domestic wastewater. The same numbers for phosphorus and potassium is 71% respectively 88%. Blackwater represents about 2% to the total domestic wastewater flow (Jönsson *et al.*, 2000).

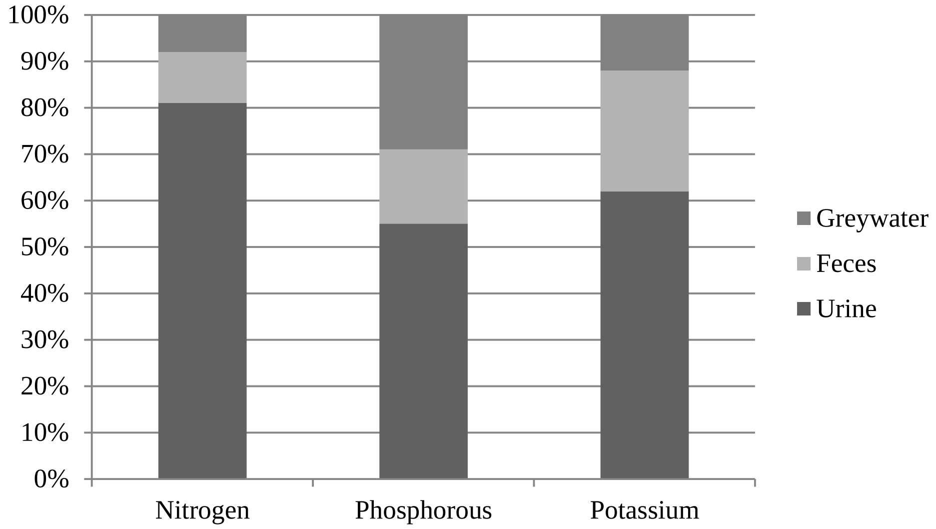


Figure 8.1. The total percentage nutrient content from domestic wastewater (Jönsson, et al., 2000).

The nutrient content in blackwater is presented in Table 8.5 in the unit mg/kg TS (Coquin, 2005). The heavy metal content in blackwater, urine, feces and greywater is represented in Table 8.6.

Table 8.5. Nutrient content in blackwater (Coquin, 2005).

Element	**Blackwater (g/kg TS)**
Tot-P	11
Tot-N	81
N-NO_3 + NO_2	n.m.
N-NH_4	n.m.
K	25

n.m. means not measured.

Table 8.6. Content of metals in blackwater, urine, feces and greywater (Frankki & Sternbeck, 2013). The highest and lowest values found in different studies.

Element	Blackwater (mg/kg P)	Urine (mg/kg P)	Feces (mg/kg P)	Greywater (mg/kg P)
Cd	8-27	0.3-2	20-23	13-22
Cr	38-2200	0.2-62	40-250	500-2300
Cu	2500-6860	68-9700	2200-4830	8200-26000
Ni	140-380	7-190	40-330	1100-1890
Pb	30-520	15-63	40-2000	340-3180
Zn	9600-27800	45-1700	21600-67200	8600-29800

8.3 Sewage sludge as fertilizer

Sewage sludge is another product that can be used as fertilizer. The use of sludge in agriculture contributes to recycling of nutrients and organic matter to the soil, but it also improves the properties of the soil in terms of structure, humus content, water holding and transmission capacity. Additionally, sludge is also usually a cheap alternative in comparison to other fertilizers (Levlin *et al*., 2001; EPA, 1999; Sommers, 1977; Korentajer, 1991).

There are also some challenges linked to the use of sludge in agriculture. Considering the fact that it has been seen that heavy metals and hazardous compounds in sludge can accumulate in the crops and be transferred to humans, the acceptance of spreading sewage-based fertilizer on farmland is not total (Levlin *et al.*, 2001; Wang *et al*., 1999; Naturvårdsverket, 2013a; Tervahautaa *et al*., 2014). The nutrient value is another challenge when using sludge as fertilizer. Sludge is considered as a low-grade fertilizer in comparison to for example artificial fertilizers, meaning that a larger amount of sludge must be spread to achieve the same required supply of nutrients. (Korentajer, 1991; Sanin *et al*., 2011).

8.3.1 Sludge characteristics

Sewage sludge contains nutrients (nitrogen, phosphorous and potassium), trace nutrients (e.g. sulphur and sodium), but also metals (e.g. zinc, copper, lead and nickel) and various forms of organic substances, pharmaceuticals and miscellaneous compounds (Snyman & Van der Waals, 2004; Emongor & Ramolemana, 2004). The quality of sewage sludge can however look very different depending on the characteristics of the wastewater entering the treatment plant, the processes at the plant and other parameters significant for the sludge production (Bresters *et al*., 1997; Snyman & Van der Waals, 2004).

8.3.1.1 Three representative sludge types

In order to get a picture of what content of nutrients and heavy metals that can be expected in sludge from different plants, the quality of sludge from different treatment plants and investigations will be highlighted in this chapter. The result from investigations presented are environmental reports (Miljörapport) from 2013 for two Swedish wastewater treatment plants (Sjölunda avloppsreningsverk and Öresundsverket) with different processes, research investigations of heavy metal content in sludge from GWWTP in 2005 and 2006 and a report of sludge quality from 77 WWTPs in South

Africa 1989. A brief description of the different treatment plants with their significant processes follows.

Production processes for the three sludge types

The treatment processes at Sjölunda WWTP consists partially of an activated sludge process but also a trickling filter for nitrification. Chemical precipitation is used to remove phosphorous from the wastewater. At Öresundsverket WWTP enhanced biological phosphorous and nitrogen removal is used to remove nutrients and is done in an activated sludge process. The investigation of sludge quality from 77 wastewater treatment plants in South Africa gives a general picture and it is therefore not possible to analyze the influence from single process parameters. The treatment processes at Valley wastewater treatment plant is extensively described in Chapter 6.

Nutrients

Table 8.7 shows the sludge quality in terms of nutrient from two Swedish wastewater treatment plants, Sjölunda reningsverk in Malmö and Öresundsverket in Helsingborg in Sweden, and from 77 different wastewater treatment plants in South Africa (Snyman *et al*., 2000; NSVA, 2013; VASYD, 2013).

Table 8.7. Nutrient content in sewage sludge from the Swedish wastewater treatment plants Sjölundaverket (VASYD, 2013) and Öresundsverket (NSVA, 2013), and a mean of 77 wastewater treatment plants in South Africa (Snyman et al., 2000).

Parameter (g/kg TS)	**Sjölunda WWTP 2013**	**Öresundsverket WWTP 2013**	**Mean value from 77 WWTPs in South African 1989**
Total-P	31	29	15
Total-N	51	58	31
NH_4-N	15	14	n.m.
K	n.m.	n.m.	2.5
S	n.m.	14	n.m.
Na	n.m.	1	n.m.

n.m. means not measured

Ngole *et al*. (2006) measured the nutrient content in three types of dry sludge from Glen Valley wastewater treatment plant (fresh, 3 months old and 36 months old). According to the results in Table 8.8, the new fresh sludge from Glen Valley wastewater treatment plant was found to have the highest nutrient content (Ngole *et al*., 2006). As seen in Table 8.7 and 8.8, the phosphorous and ammonium content at Glen Valley are significantly lower than in the two Swedish WWTPs.

Table 8.8. Nutrient content of Glen Valley dry sludge (Ngole, et al., 2006)

Parameter	**Glen Valley Drying bed-sludge, 2006**		
(g/kg TS)	**New sludge**	**3 month old sludge**	**36 month old sludge**
Total-P	9.4	7.7	7.3
Total-N	55	45	34
NH_4-N	1.4	0.6	0.6
NO_3-N	1.7	0.6	0.5
Organic matter (%)	41	32	23

Heavy metals

Table 8.9 shows the heavy metal content in sludge from two Swedish wastewater treatment plants, Sjölundaverket in Malmö and Öresundsverket in Helsingborg, and from 77 different wastewater treatment plants in South Africa in the unit mg/kg TS.

It is seen that the values for Sjölunda WWTP and Öresundsverket WWTP is quite similar but the sludge from Sjölunda WWTP seems to be slightly higher for almost all the metals. According to Balmér (2001) the use of chemical precipitation agents in the wastewater treatment affects both the quantity and heavy metal content of the sludge. As mentioned in Chapter 5.4, chemical precipitation agents often contain heavy metals which can be reflected in the sludge (Balmér, 2001). The metal contents in sludge from the South African study are higher for all measured metals.

Table 8.9. Heavy metal content in sludge from Sjölundaverket (VASYD, 2013) and Öresundsverket (NSVA, 2013), and sewage sludge from South Africa (Snyman et al., 1685)

Parameter (mg/kg TS)	**Sjölunda, 2013**	**Öresundsverket, 2013**	**South Africa, 1989**
As	n.m.	5	7
Cd	1.2	0.8	13
Cr	30	28	551
Co	6.5	3.9	n.m.
Cu	480	410	655
Pb	30	20	460
Hg	0.6	0.6	5
Ni	28	20	155
Ag	2.2	2.4	n.m.
Zn	590	600	2054
Al	12500	n.m.	n.m.
Fe	62300	n.m.	n.m.

n.m. means not measured

Analyses of heavy metal content in sludge have been done at Glen Valley in 2005 and 2006. The analysis of sludge from the drying beds at Glen Valley WWTP in Ngole *et al.* (2006) showed that the heavy metal content in sludge with different ages were relatively similar. In Nkegbe & Koorapetse (2005) not only the sludge quality in terms of heavy metal content was stated, it was also found that the concentration of four chosen heavy metals (lead, nickel, zinc and iron) were higher in the sludge than in the effluent (Nkegbe & Koorapetse, 2005). The results for these investigations are shown in Table 8.10.

Table 8.10. Content of Heavy Metals in the Sludge from the drying beds at Glen Valley wastewater treatment plant (Nkegbe & Koorapetse, 2005; Ngole, et al., 2006).

Parameter	**Nkegbe et al. (2005)**	**Ngole et al. (2006)**		
(mg/kg TS)	**Dry sludge, Unknown age**	**New Sludge**	**3 month old sludge**	**36 month old sludge**
As	0.8-1.2	15	11	3.9
Cd	n.m.	1.3	1.5	1.1
Cr	n.m.	5.0	5.8	4.9
Cu	n.m.	63	120	110
Ni	28-33	13	23	18
Pb	450-480	210	300	230
Zn	290-450	350	400	340
Mn	n.m.	110	270	250

n.m. means not measured

Micropollutants

In order to get an idea of the micropollutant content in sludge, analyses from Sjölundaverket (VASYD, 2013) and Öresundsverket (NSVA, 2013) are presented in Table 8.11. The result from the two plants are similar but it can be seen that Sjölunda WWTP has higher values of nonylphenol and PAH than Öresundsverket WWTP. The variation of these components may though be different at different treatment plants, both in terms of quantity and quality, since up to 250 different organic substances and over 100 pharmaceuticals have been found in sludge from Sweden (Frankki & Sternbeck, 2013).

Table 8.11. Micropollutant content in sludge from Sjölundaverket (VASYD, 2013) and Öresundsverket (NSVA, 2013)

Parameter (mg/kg TS)	**Sjölunda WWTP 2013**	**Öresundsverket WWTP 2013**
Nonylphenol	16	9.1
PAH	1.6	1.1
PCB	0.03	0.03

8.3.2 Limits and regulations of sludge use in agriculture

There are several different limits and guidelines around the world that regulates how the quality of the sludge should be in order for it to be used as fertilizer on farmland. For the moment, there is no legislation or guidelines found regulating the sludge quality for use in agricultural purposes in Botswana. Guidelines and regulations from the European Union, South Africa and Sweden have though been compared.

The agricultural use of sludge within The European Union is regulated by the EG-directive 86/278/EEG and can be seen in Table 8.12 and 8.13. Since this regulation is almost 30 years old many member countries in the EU have nowadays their own legislation. The EG-directive 86/278/EEG is about to be revised (European Commission, 2015).

The agricultural use of sludge in South Africa is regulated according to the guide "Permissible Utilization and Disposal of Sewage Sludge, Edition 1" from 1997 (Snyman *et al*., 2000). The guide aims to assist and guide organizations involved in sludge treatment to promote safe handling, disposal and utilization of sewage sludge. According to the guide, sewage sludge is classified within four types: A, B, C and D, where D can be used as fertilizer and has the highest hygienic quality and highest requirements on heavy metal contents in sludge (Water Research Commission, 1997). Read more about the sludge classification in South Africa in Appendix I.

In Sweden the limits controlling the sludge quality when used in agriculture is regulated by the Swedish constitution called SFS 1998:944.

Table 8.12. Limits for metals brought to agriculture land by sewage sludge in Sweden, EU and South Africa (EG, 1986/278/EEG; SFS, 1998:944; Water Research Commission, 1997)

Parameter (mg/kg TS)	Limits Sweden	Limits EU	Limits South Africa
As	-	-	15
Cd	2	20-40	15.7
Co	-	-	100
Cr	100	1000-1500	1750
Cu	600	1000-1750	50.5
Ni	50	300-400	200
Pb	100	750-1200	50.5
Zn	800	2500-4000	353.5

Table 8.13. Limits for metals brought to agriculture land by sewage sludge in Sweden, EU and South Africa. (EG, 1986/278/EEG; SFS, 1998:944; Water Research Commission, 1997).

Element (g/ha,y)	Limits Sweden	Limits EU	Limits South Africa
Cd	0.75	150	125.6
Cr	40	4000	14000
Cu	300	12000	404
Hg	1,5	100	80
Ni	25	3000	1600
Pb	25	15000	404
Zn	600	30000	2828

There are guideline limits for the micropollutants measured in Table 8.11 in Sweden, but there is an ongoing debate that there should be limits for an increased number of substances. The guideline limits can be seen in Table 8.14 and are an agreement between Farmers national organization, Swedish water association and Swedish EPA (LRF, Svenskt Vatten och Naturvårdsverket) (Månsson, 2014).

Table 8.14. Guideline limits for sludge that are spread on farmland in Sweden (Månsson, 2014).

Substance	**Limit (mg/kg TS)**
Nonylphenol	50
PAH	3
PCB	0.4

9 Improvements of sludge quality

The quality of sludge can be improved by using several different methods. The aim with this quality improvement in this point of view is to higher the nutrient content and eliminate hazardous compounds in order to higher the fertilizer potential. To start with, there are several treatment techniques to remove heavy metals from the wastewater or sludge; struvite enhancement, activated carbon treatment and combustion. Many of these techniques are though very expensive and can only eliminate the contents of hazardous compounds in a certain stream. Apart from treatment techniques, source tracking is an efficient and relatively cheap method to improve the quality of the sludge but also to remove contaminants from the effluent stream (Sanin *et al.*, 2011).The idea behind source tracking is to eliminate the content of hazardous compounds already at the source, before it reaches the wastewater sewer network.

Below follows a brief description of different treatment techniques and thereafter is the concept of source tracking discussed.

9.1 Treatment techniques

This chapter will describe some of the most common treatment techniques for nutrient recovery from wastewater and sludge; Phosphorous recovery from sludge ash, activated carbon, struvite enhancement and blackwater separation systems.

Phosphorous recovery from sludge ash
A treatment method to separate phosphorous from sludge is to incinerate the sludge and extract the nutrient from the ash. With this method, both nitrogen and organic matter together with micropollutants are combusted. This process produces a residual ash containing phosphorous and some heavy metals. In order to extract the phosphorous from the ash, different processes can be used including either chemicals as acid, chloride or calcium or thermal treatment (Levlin *et al.*, 2014; Carlsson *et al.*, 2013). With this method, up to 95% of the phosphorous from the incoming wastewater can be recovered if the treatment plant has processes to separate the phosphorous to the sludge (Tideström *et al.*, 2009). In order to incinerate sludge, the water content need to be below 40% but are in the most cases much higher for treated sludge (Östlund, 2003).

Activated carbon
The adsorption of metals in activated carbon is another way to improve the quality of sludge. With this method, wastewater passes through a filter bed of granular activated carbon where hazardous compounds can be removed since they adsorb to the activated carbon (Donau Carbon, 2015). The method could be a cheap alternative, since it can be produced by natural waste and by-product materials (Kadirvelu *et al.*, 2001).

Struvite enhancement
Struvite is a crystalline compound with the chemical formula $MgNH_4PO_4 * 6\ H_2O$, containing nitrogen, phosphorous and magnesium (Wilsenach *et al.*, 2003). The struvite compound precipitate spontaneous as a salt at pH 7-11 when all the three components magnesium, nitrogen and phosphorous occur in water. In wastewater, magnesium is the limiting factor and therefore the precipitation of struvite can be enhanced by adding magnesium to a stream in the wastewater treatment plant. Struvite is very pure and do not contain any hazardous compounds (Fransson *et al.*, 2010).

Approximately 20-25% of the phosphorous and a small part of the nitrogen can be recovered from the wastewater (Tideström *et al*., 2009). The struvite process works best when the treatment plant has an enhanced biological phosphorous removal process (Carlsson *et al*., 2013).

Separated blackwater
A large part of the nutrients from human wastes are found in the blackwater. About 80% of the phosphorous and 90% of the nitrogen (Jönsson *et al*., 2000). When separating blackwater from the remaining domestic wastewater stream, nutrients do not get diluted and contaminated by streams that may obstruct the recycling (Jönsson *et al*., 2013).

9.2 Source tracking

Source tracking is a way to prevent hazardous and environmentally toxic compounds to end up in the wastewater system. The idea behind source tracking is to trace these compounds already at the source and eliminate them so that the wastewater entering the wastewater treatment plant does not contain any harmful and untreatable elements (Svenskt Vatten, 2014). It can be cheaper and easier to eliminate the metals at the sources, instead of remove them in the sludge (Sanin *et al*., 2011). Below the work with source tracking in Botswana and Sweden are described.

9.2.1 Source tracking in Botswana

The work with source tracking in Botswana is mainly driven by The Water Utilities Corporation and is embodied in the Trade Effluent Agreement (TEA). The TEA aims to regulate and control the industrial wastewater before it enters the sewer system.

When industrial effluent with hazardous compounds is mixed with domestic water, harmful substances can be harder to treat efficiently since they are diluted with non-contaminated water. The WUC infrastructure director Mr. Senai (2014) said during a workshop that in some cases it has been observed that companies are dumping oil, used paint, dyes, chicken feathers, cattle, goat organs among others directly to the sewer system. The sewer system and the treatment plant is not designed to transport and treat industrial effluent containing chemicals, heavy metals, fats, grease etc. and therefore the work with avoiding these substances coming to the sewage network is prioritized in Botswana (Tebogo, 2014; Motoma, 2015).

Trade Effluent Agreement (TEA)
The WUC together with other authorities developed the TEA in order to ensure that industrial wastewater that are discharged to the sewer network meet the set quality standards, not cause harm to the sewer system or public health and is possible to treat properly in the WWTP (Tebogo, 2014). The agreement is used to manage and regulate the effluent from industries. The agreement describes the responsibilities and obligations for the WUC and the industries regarding the effluent quality discharged to the sewer system. The acceptable effluent discharge limits for some metals into the public sewer system can be seen in Table 9.1, whereas the whole list can be seen in Appendix II (Water Utilities Corporation, 2012).

Table 9.1. Acceptable discharge limits into the public sewer system in Botswana (Water Utilities Corporation, 2012).

Parameter	Content (mg/l)
As	5
Cd	5
Cr (Tot)	10
Co	20
Cu	5
Ni	20
Pb	5
Zn	20

Besides responsibilities and obligations, fees and charges for industries with an effluent not meeting the requirements are also described in the agreement. The agreement also prohibits industrial effluent discharge to the stormwater system in Botswana. WUC gives recommendations and advices to industries. An example is to advice all industries and organizations that produce greasy effluent to install grease traps (Water Utilities Corporation, 2012).

The work with the TEA is divided in seven different activities: registration, sampling, analysis, reporting, invoicing, compliance & policing and review & verification. The responsibility for the different activities is thereafter divided between department units involved in the work with the source tracking. The activities stated above are briefly described in Table 9.2.

Table 9.2. Trade Effluent Agreement Structure (Water Utilities Corporation, 2012)

Activity	Explanation
Registration	Identification of industries, management with signing of the trade effluent agreement, request of Environmental Management Plan (EMP) for new connections
Sampling	Management of sampling from industries connected to the sewer system
Analysis	Analyze of samples
Reporting	Distribute results of sampling to credit control and industries, address non conformities
Invoicing	Charge the customer
Compliance & Policing	Conduct random visits of industries, ensure compliance, Receive EMP from industries
Review and verification	Review meetings

In order to control the effluent discharge from the industries, the WUC demands sampling and analysis of the wastewater from the industries. It is the industry's responsibility to organize the quality controls after signing the agreement. The cost of the sampling is free of charge for the first control, but thereafter the owner of the industry has to pay. Also, if pretreatment is needed or if the quality standards for releasing wastewater to the sewer network are not met, the industry owner has to pay. The controls can both be done by WUC or an accredited lab. All parameters in Table IIb in Appendix II are measured during the controls, including heavy metals (Motoma, 2015).

The WUC has distributed about 680 draft agreements in Botswana but only 20 companies have signed the agreements in January 2015. The WUC has noticed some negative attitudes towards the agreement from industries which is explained by the extra costs in terms of pretreatment or sampling that the agreement could contribute to (Motoma, 2015). In order to have more industries signing the agreement, the WUC has engaged stakeholders which in various ways highlight its importance (Tebogo, 2014).

Since the implementation of the agreement started recently, changes in the sludge quality or wastewater characteristics in the sewer system have yet not been investigated. The work is focused on the identification of the different industries connected and their processes (Motoma, 2015).

9.2.2 Source tracking in Sweden

The most important legislations about the work of source tracking in Sweden are the national water regulation, the environmental code, REVAQ and REACH. These four regulations are described below.

The Environmental code

The Environmental code aims to support sustainable development and involves rules for classification of businesses that are environmentally hazardous, use chemical products, produce hazardous wastes etc. According to the code, the municipal wastewater companies have a chance to determine whether and how the wastewater from a property with the classification environmentally hazardous business may be connected to the sewer system. The wastewater company can for example require pretreatment or impose other requirements for connection (Svenskt Vatten, 2014).

The national water regulation

The National Water Regulation (Lagen om allmänna vattentjänster, SFS 2006:412) describes a national framework for the responsibilities and obligations between the subscriber and the municipal wastewater company. It is a governing law and describes how the municipal wastewater company should work with regulations to prevent hazardous and environmentally toxic compounds to end up in the sewage network and the wastewater treatment plants (§ 18, 21 and 22). It also says that the municipality is not bound to allow a connection to the sewer network if the wastewater that is discharged from the property of concern could harm the sewage network or cause problems to meet the standards of the treatment plant (i.e. does not have household-characteristics)(Prop. 2005/06:78, chap 5:10) (Svenskt Vatten, 2012).
If the discharged wastewater does not meet the requirements, it must either get an initial treatment before it enters the sewer network or be separated and totally treated in a separate plant. (Svenskt Vatten, 2012); (Levlin *et al*., 2001). The municipalities can decide their limit values for discharged wastewater to the sewer network based on general discharge limits given in the national water regulation. Discharge limits for a municipal wastewater company in south Sweden can be seen in Table 9.3.

Each municipality is also allowed to explain further regulations on how the municipal wastewater management system should be used in the regulation called ABVA (Allmänna bestämmelser för brukande av den allmänna vatten- och avloppsanläggningen) (Svenskt Vatten, 2012).

Table 9.3. Maximum discharge limits for wastewater into the sewer network in a municipality in southern Sweden, (NSVA, 2015)

Parameter	Concentration (mg/l)
Cd	0.0005
Cr (+6)	0.01
Cr (Total)	0.05
Cu	0.5
Ni	0.05
Pb	0.05
Zn	0.5

REVAQ

In order to improve and speed up the process with source tracking, a certification system called REVAQ is used voluntarily by wastewater treatment plants. The main objective with the certification system is to reduce the discharge of hazardous and environmentally toxic compounds from households and industries. That is done in order to ensure good quality of the sludge from the treatment plants and to preserve the natural environment of the Swedish receiving waters (NSVA, 2015). REVAQ is a collaboration between the wastewater treatment plants, farmers national association and Swedish authorities within water, trading and agriculture: (Svenskt vatten, Lantbrukarnas Riksförbund, Lantmännen, Svensk Daglig- varuhandel and Naturvårdsverket) (Svenskt Vatten, 2014). About half of the Swedish population is connected to a wastewater treatment plant certified by REVAQ (Finnson, 2014).

REVAQ implies work with source tracking and actions for continuous improvement of the sludge and effluent water quality. The information from the treatment plants about sludge and effluent quality and work with REVAQ must be public. All wastewater treatment plants certified by REVAQ are obliged to control 60 predefined trace elements in the sludge. The result of the sludge quality assessments must be published every year and is also compared with the target stated by REVAQ. These targets are individual for every treatment plant and aims to strive for continuous improvement of the sludge quality. The work is controlled by an extern inspector to ensure that all policies within REVAQ are followed (Finnson, 2013).

With a study of sludge quality from REVAQ-connected wastewater treatment plants, a gradual reduction of metals in the sludge could be seen during a period of 10-year (Kärrman *et al.*, 2007).

REACH

REACH stands for Registration, Evaluation, Authorization and Restriction of Chemicals. It is the European Union's chemical legislation which aims to increase the knowledge about the use of chemicals and their properties on the European market. REACH requires companies that use chemicals to identify and register the environmental and health effects of these chemicals (KemikalieInspektionen, 2011a).

10 Quality of the sludge from GWWTP

The quality of the sludge from Glen Valley wastewater treatment plant was investigated at five different sites, see Chapter 1.5. Below follows observations during the sampling and results from quality analysis of the sludge from the plant.

10.1 Observations during sampling

To understand the result better, a brief presentation of the situation at the five sampling sites are presented in this section.

At sampling point 1, the primary sludge was collected in an open buffer tank where the sludge is pumped after the anaerobic digestion. The sampled sludge had been in the tank for around three weeks due to maintenance issues. The sludge was sampled in different levels in the tank, see Figure 10.1.

Figure 10.1. a) Sampling of primary sludge from buffer tank after anaerobic digestion, b) Anaerobic digestion tanks

At sampling point 2, the secondary sludge was collected from the top of the aerobic digestion tank. There was much foam and the sludge was watery, see Figure 10.2.

Figure 10.2. a) Sampling of secondary sludge from the aerobic digestion, b) Aerobic digestion tank

The dry fresh sludge was collected at sampling point 3, outside the dewatering plant and the sludge was around three weeks old. It was a pile that was left at the loading area and the sludge was dry, see Figure 10.3.

Figure 10.3. Sampling site for dry fresh sludge after the dewatering tank, sampling point 3.

At sampling point 4 and 5, dry sludge was collected from the sludge piles. There were two stringent layers and sample 4 was collected from the top layer. It was also very dry. The operator assumed that this sludge was from the secondary anaerobic digester, meaning only primary sludge due to maintenance issues. Sample 5 was collected from the bottom layer and was assumed to origin from the same basin, but put there earlier. How much earlier was unknown. The two layers are seen in Figure 10.4.

Figure 10.4. Sampling site for old dry sludge (top of the pile) and older dry sludge (bottom of the pile). Top layer is above the white stripe and bottom layer is below the white stripe.

10.2 Sludge sample analysis

Result from the sludge sample analysis is described in this chapter.

10.2.1 Physiochemical parameters

The physiochemical parameters for the sludge at Glen Valley wastewater treatment plant is shown in Table 10.1. The table shows temperature, pH, conductivity, TS and VS of TS. The temperature, pH and conductivity were only measured for the wet sludge types.

Table 10.1. Physiochemical parameters of the sludge from GWWTP

Parameter	Primary sludge	Secondary sludge	Fresh dry sludge	Old dry sludge	Older dry sludge
Temp (°C)	29	19	-	-	-
pH	6.8	5.2	-	-	-
Conductivity (mS/cm)	4.5	4.4	-	-	-
TS (%)	6.7	2.8	96	96	24
VS of TS (%)	56	57	53	55	81

10.2.2 Nutrient content

The nutrient content in the sludge samples can be seen in Table 10.2. The secondary sludge sample had the highest nutrient value for all nutrients except calcium. The lowest nutrient content is found in the dry sludge types except for calcium. This is results from analysis S, performed in Sweden.

Table 10.2. Nutrient content in the five sludge samples from GWWTP according to analysis S.

Parameter (g/kg TS)	Primary sludge	Secondary sludge	Fresh dry sludge	Old dry sludge	Older dry sludge
Tot-P	19	23	8.8	8.9	8.9
Tot-N	40	44	33	32	33
K	4.1	6.2	2	1.6	1.8
Ca	22	21	20	23	24
Mg	5.3	6.7	3	3.3	3.6
Mn	0.3	0.3	0.1	0.2	0.2
Na	2.3	4.5	0.4	0.4	0.8
SO_4	9.5	12	4.5	1.9	4.6

10.2.3 Heavy metal content

The metal content in the sludge types are seen in Table 10.3 and Table 10.4 according to analysis B and S respectively. The metal content in the primary sludge sample is in almost all cases slightly higher than in the secondary sludge sample. In the three dry sludge samples it is the old dry sludge that has the highest metal content for all measured metals. See Figure 10.5-10.8 for metals exceeding the chosen limits.

Table 10.3. Metal content in the five sludge samples from GWWTP according to analysis B.

Parameter (mg/kg TS)	Primary sludge	Secondary sludge	Fresh dry sludge	Old dry sludge	Older dry sludge
Al	1100	990	790	1000	1200
As	77	28	53	40	66
Cd	1.3	0.2	0.2	0.1	0.3
Co	2.1	1.3	1.3	1.3	1.2
Cr	5	3.7	3.5	4.6	4.9
Cu	64	56	43	56	58
Fe	1400	810	580	1200	1310
Ni	3.5	3	2.3	2.6	2.8
Pb	31	22	33	31	34
Zn	190	110	110	130	130

Table 10.4. Metal content in the five sludge samples from GWWTP according to analysis S.

Parameter (mg/kg TS)	Primary sludge	Secondary sludge	Fresh dry sludge	Old dry sludge	Older dry sludge
Al	11900	11500	11800	12300	11800
As	5	3.9	3.5	3.9	4.2
Cd	1	1	1.2	1.2	1.2
Co	3.5	3.6	3.9	4	3.8
Cr	45	39	43	45	43
Cu	560	570	490	520	490
Fe	10400	9700	11200	11200	11200
Ni	40	38	37	37	36
Pb	300	260	270	250	240
Zn	1200	1030	1000	1000	970

It can be seen in Table 10.3 and 10.4 that the metal content is very different depending on analysis method. This is further illustrated in Figure 10.5-10.8 and is discussed in chapter 12.

The metal content in the sludge is also shown in Table 10.5, but in relation to the content of phosphorus in the sludge. This is only for analysis S, where the nutrients also were measured.

Table 10.5. Metal content in relation to phosphorous value measured according to analysis S.

Parameter (g/kg P)	Primary sludge	Secondary sludge	Fresh dry sludge	Old dry sludge	Older dry sludge
Al	630	510	1350	1380	1330
As	0.3	0.2	0.4	0.4	0.5
Cd	0.1	0.1	0.1	0.1	0.1
Co	0.1	0.1	0.4	0.5	0.4
Cr	2.4	1.7	4.9	5	4.8
Cu	30	25	56	58	55
Fe	550	430	1270	1260	1260
Ni	2	1.7	4.2	4.2	4
Pb	16	11	30	28	26
Zn	64	45	110	110	110

Since the metals arsenic, copper, lead and zinc have exceeded the limits from South Africa or Sweden regarding sludge quality in the use as fertilizer, these are presented in Figure 10.5, 10.6, 10.7 and 10.8.

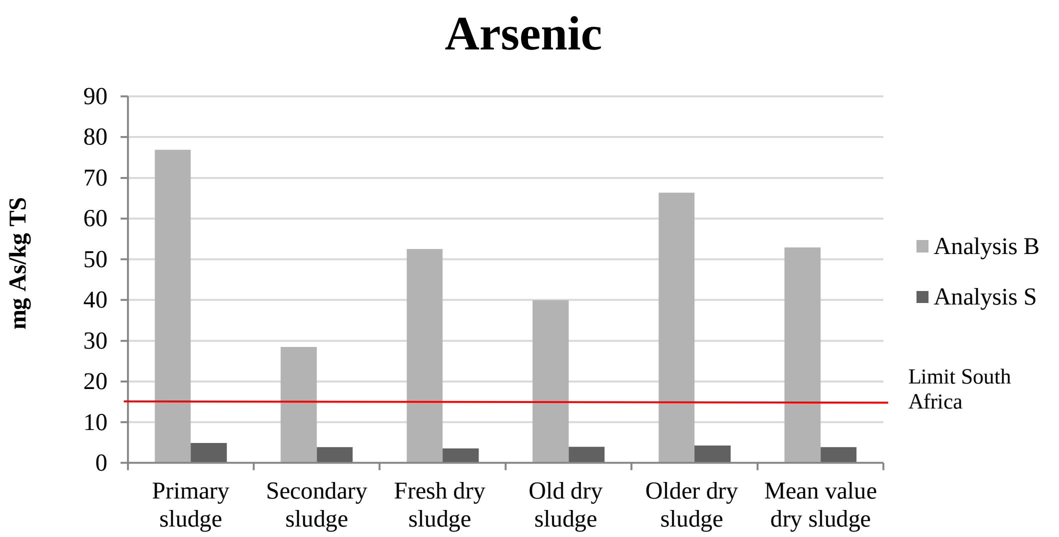


Figure 10.5. Arsenic content in the different sludge types from GWWTP according to analysis B and S, respectively. There were no found limits from Sweden or EU.

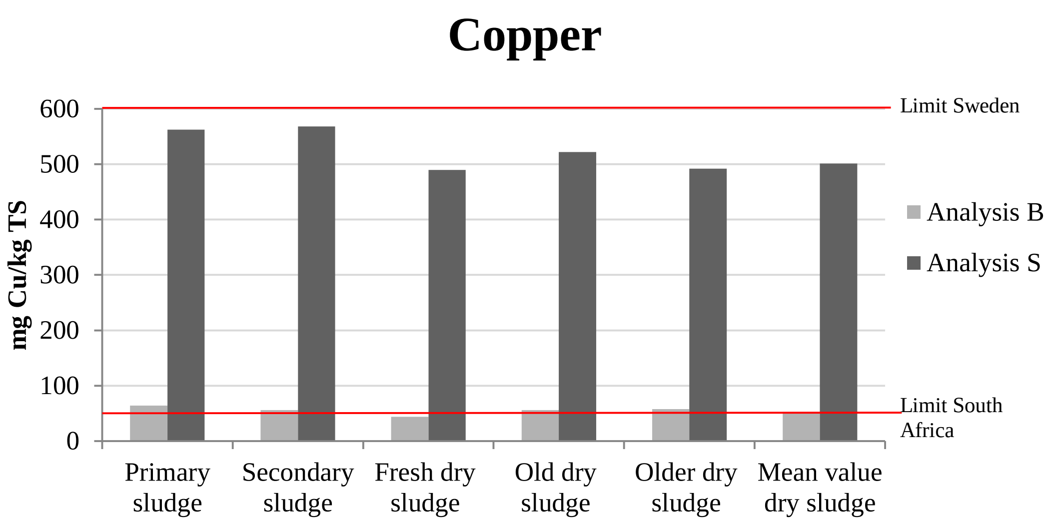


Figure 10.6. Copper content in the different sludge types from GWWTP according to analysis B and S, respectively. The limit from EU is 1000-1750 mg/kg TS and is therefore not shown in this table.

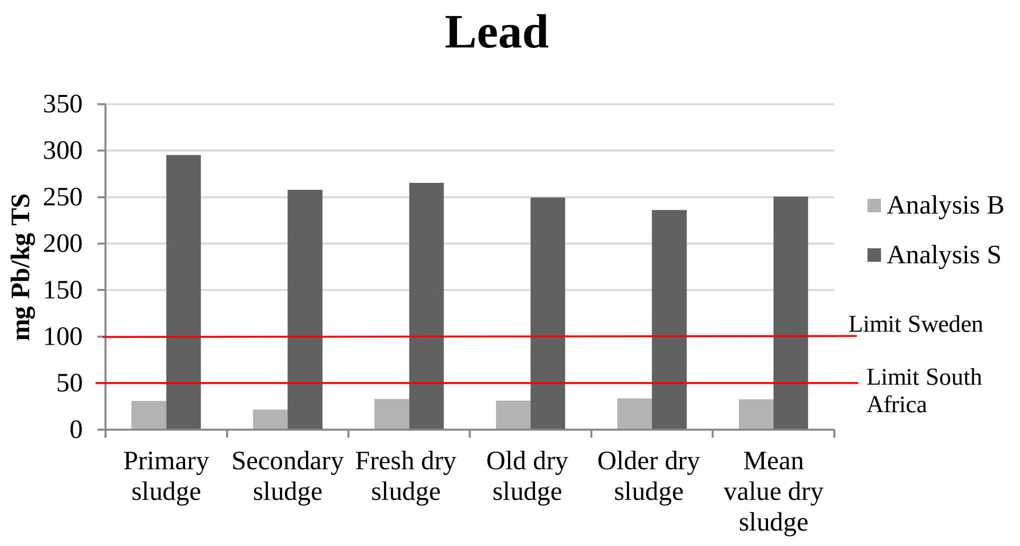


Figure 10.7. Lead content in the different sludge types from GWWTP according to analysis B and S, respectively. The limit from EU is 750-1200 mg/kg TS and is therefore not shown in this table.

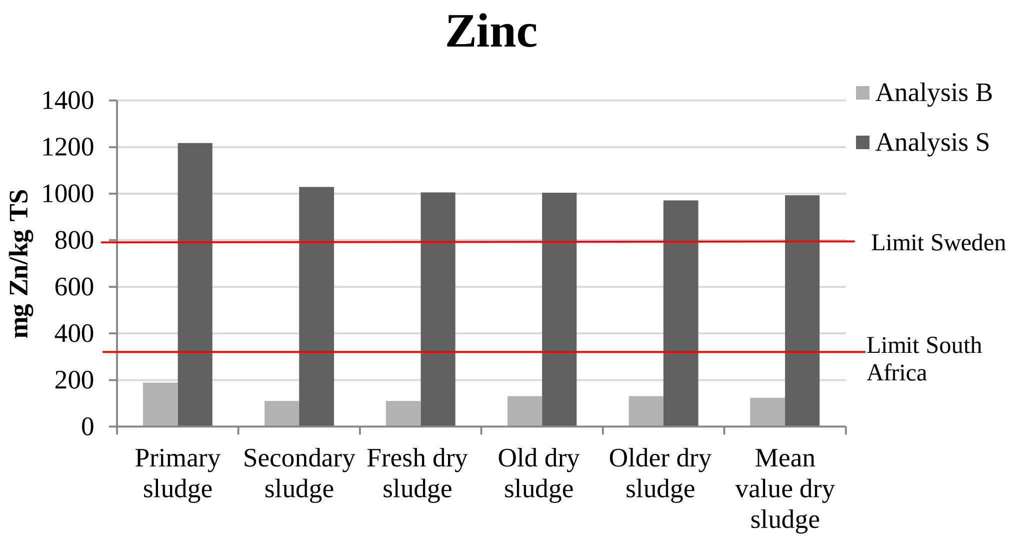


Figure 10.8. Zinc content in the different sludge types from GWWTP according to analysis B and S, respectively. The limit from EU is 2500-4000 mg/kg TS and is therefore not shown in this table.

11 Comparative analysis

To make a qualitative assessment of the sampled sludge from GWWTP it is here compared to regulations, other fertilizers and other sludge types. Since the three dry sludge types (from sample points 3, 4 and 5) have quite similar nutrient and heavy metal values, they are presented as one mean value. The primary and secondary sludge samples are not included in the comparison since they are not finished products and the dry sludge types are more similar to other fertilizers. Both the sludge analysis B and S is represented in the comparison to the other studies.

11.1 Nutrient content

The nutrient value in the sludge samples from GWWTP is compared to other fertilizers and other sludge types. Nutrient content in the sludge was not measured in analysis B and therefore it is only analysis S result in the comparisons below.

11.1.1 Comparison with other fertilizers

The nutrient content in the sampled sludge is here compared to artificial fertilizers, digestate, manure and other sludge analysis.

As seen in Table 11.1, the artificial fertilizers have the highest nutrient value. The dry sludge sampled from GWWTP has the lowest nutrient value for all measured nutrients except nitrogen, where cow manure has the lowest value. Overall the cow manure is in the same range as the dry sludge except for potassium and sodium. Blackwater are in the same range for phosphorous but have higher nitrogen and potassium values.

Table 11.1. Nutrient content in different types of fertilizers (Steineck et al., 1999; Ljung et al., 2013; Yara, 2015; Coquin, 2005).

Parameter (g/kg TS)	Dry sludge GWWTP analysis S	Artificial fertilizer Yara Mila 21-4-7	Artificial fertilizer Yara Mila 27-2-3	Co-digestate	Cow manure	Blackwater
Tot-P	8.9	36	20	16	9	11
Tot-N	33	210	270	150	30	81
K	1.8	66	30	46	28	25
Mg	3.3	9	0	n.m.	5.9	n.m.
Na	0.5	n.m.	n.m.	n.m.	5	n.m.
SO4-S	3.7	30	25	n.m.	5	n.m.

n.m. means not measured

11.1.2 Comparison with other sludge types

When comparing the sludge samples from GWWTP with sludge from two Swedish plants (Sjölunda and Öresundsverket), the average from 77 South African plants and samples from 2006 at GWWTP it is seen that the phosphorous content in sludge from GWWTP are lower than for sludge from Sweden and South Africa. The nitrogen content is low in comparison to Swedish wastewater treatment plants and in the samples from the study at GWWTP in 2006. The potassium content is in approximately the same range as in the South African sludge, see Table 11.2.

Table 11.2. Nutrient content in different types of sludge (Snyman, et al., 2000; NSVA, 2013; VASYD, 2013; Ngole, et al., 2006)

Parameter (g/kg TS)	Dry sludge GWWTP analysis S	Dry sludge GWWTP 2006	Sjölunda WWTP	Öresundsverket WWTP	Mean value from WWTPs South Africa
Tot-P	8.9	9.4	31	29	15
Tot-N	33	55	51	58	31
K	1.8	n.m.	n.m.	n.m.	2.5
Na	0.5	n.m.	n.m.	1	n.m.
SO_4	3.7	n.m.	n.m.	14	n.m.

n.m. means not measured.

11.2 Heavy metal content

The heavy metal content in the sampled sludge is compared to regulating limits, other fertilizers and other sludge types.

11.2.1 Comparison with limits for sludge use in agriculture

The limits are compared to the result of metal content in the sludge samples from GWWTP according to analysis B and S.

It can be seen in Figure 10.5, 10.6, 10.7 and 10.8 that arsenic and copper exceeds the metal content in sludge for analysis B according to South Africa’s limits. For analysis S it can be seen that copper, lead and zinc exceeds the South African limits. The content of lead and zinc exceeds both the South African and the Swedish limits. The measured content of the exceeded metals from the sampled sludge are significantly higher than the limits in South Africa, see Table 11.3 for the comparison.

Table 11.3. Metal content in sludge samples from GWWTP according to analysis B and analysis S. and limits for sludge quality for agricultural purposes in Sweden, EU and South Africa (EG, 1986/278/EEG; SFS, 1998:944; Water Research Commission, 1997).

Parameter (mg/kg TS)	Dry sludge GWWTP analysis B	Dry sludge GWWTP analysis S	Limits Sweden	Limits EU	Limits South Africa
As	53	3.9	n.m.	n.m.	15
Cd	0.2	1.2	2	20-40	15.7
Co	1.3	3.9	n.m.	n.m.	100
Cr	4.3	44	100	1000-1500	1750
Cu	52	500	600	1000-1750	50.5
Ni	2.6	37	50	300-400	200
Pb	33	250	100	750-1200	50.5
Zn	120	900	800	2500-4000	353.5

n.m. means not measured.

11.2.2 Comparison with other fertilizers

The metal content in the dry sludge samples according to analysis B and S are compared to other types of fertilizers in Table 11.4. The sludge sample’s metal content in relation to phosphorous are compared to a commercial P-fertilizer in the unit g metal/kg nutrient. It can be seen in Table 11.4 that the metal content in the sludge sample from GWWTP are much higher than in the artificial fertilizer except for cadmium according to analysis B. Same conclusion can be made when looking at analysis S. In comparison to cow manure the sludge from GWWTP have higher metal content for all metals in analysis S but cow manure have higher concentrations for all metals except for lead in comparison to analysis B.

Table 11.4. Mean concentrations of heavy metals for different fertilizers, related to phosphorous (Tervahautaa, et al., 2014; Remy & Ruhland, 2006; Frankki & Sternbeck, 2013).

Element (g/kg P)	**Dry sludge GWWTP analysis B**	**Dry sludge GWWTP analysis S**	**P- fertilizer as P_2O_5**	**Cow manure**	**Blackwater**
As	6	0.4	0.01	Not detected	n.m.
Cd	0.1	0.1	0.04	0.03	0.018
Cr	0.5	4.9	0.54	1.2	1.1
Cu	5.9	56	0.09	14	4.7
Ni	0.3	4.1	0.08	1.5	0.26
Pb	3.7	28	0.07	0.7	0.28
Zn	14	110	0.8	26	19

n.m. means not measured.

If the comparison is made in the unit mg metal/kg TS, cow manure has in most cases a lower concentration of metals than the sludge samples from GWWTP, see Table 11.5. For analysis B, the nickel concentration is about the same as for cow manure and the concentration for zinc is higher for cow manure. For analysis S all values are higher than the cow manure example.

Table 11.5. Metal concentration in sludge from GWWTP according to analysis B, analysis S and cow manure in mg/kg TS (Steineck et al., 1999)

Element (mg/kg TS)	**GWWTP analysis B**	**GWWTP analysis S**	**Cow manure**
As	53	4	n.m
Cd	0.18	1	0.16
Cr	4.3	44	2.8
Cu	52	500	31
Ni	2.6	37	3
Pb	33	250	0.69
Zn	120	990	170

n.m. means not measured.

11.2.3 Comparison with other sludge types

In Table 11.6 it can be seen that in the analysis of sludge from GWWTP, the highest heavy metal content tends to be in the sludge measured in 2015 at analysis S. There is no clear relation for either analysis B or S to the earlier analysis according to the results shown in Table 11.6.

Table 11.6. Heavy metal content in sludge from GWWTP according to analysis B (2015A) and analysis S (2015B) in 2015, analysis from 2006 and 2005, Sjölundaverket, Öresundsverket and 77 WWTP in South Africa (Snyman et al., 1685), (Nkegbe & Koorapetse, 2005; Ngole et al., 2006)

Element (mg/kg TS)	GWWTP analysis B	GWWTP analysis S	GWWTP 2006	GWWTP 2005	Sjölunda, 2013	Öresunds-verket 2013	South Africa 1989
As	53	4	15	0.8-1.2	n.m.	5	7
Cd	0.2	1	1.3	n.m.	1.2	0.8	13
Co	1.3	4	n.m.	n.m.	6.5	3.9	n.m.
Cr	4.3	44	5	n.m.	30	28	550
Cu	52	500	63	n.m.	480	410	660
Ni	2.6	37	13	28-33	30	20	460
Pb	33	250	210	450-480	28	20	160
Zn	120	990	350	290-450	590	600	2050

n.m. means not measured

12 Discussion

In this chapter the results from literature and field study are discussed. The discussion is divided into four parts; Quality of sludge from GWWTP, The management and use of sludge, Sludge quality improvements and lastly a broader discussion.

12.1 Quality of the sludge from GWWTP

The discussion of sludge quality is further divided into different parts; Simplifications, Analysis procedure, Sludge quality (nutrient value, heavy metal content, physiochemical parameters and pathogens) and possible improvements.

12.1.1 Simplifications

It is important to highlight that the analysis is based on one single sampling occasion regarding the result of the sludge quality. Because of this, only an indication of the reality could be said. More analyses have to be done in order to determine the actual status of the sludge quality. To include seasonal and weekly variations in sludge quality, it would be preferable to sample during several days in a week and preferably at different times of the day, but also over a longer period of time.

Another influencing factor not taken into account is the retention time for the different treatment processes within the treatment plant. Since the different types of sludge have been within the treatment plant for different long time, a reliable mass balance of metals or nutrients cannot be done. The quality of the fresh dry sludge cannot in a correct way be compared with the primary or secondary sludge since they may origin from wastewater with different origin and characteristics.

12.1.2 Analysis procedure

Two different analysis methods were used in this study and the result of metal content in the sludge showed different result for the two methods. One reason for this can be the laboratory experience of the performer of the analysis. The authors of this study performed the analysis B with assistance from technicians and other students at University of Botswana, while professional laboratory staff that works with soil and sludge analysis every day performed the analysis S. The authors did this analysis for the first time with this study. The type of digestion method with the acid preparation to extract metals from the solid to liquid phase can also have an impact on the result.

Both results from analysis B and S are compared to other fertilizers, sludge types and regulations, but to look at a worst case scenario, analysis S can be chosen since the result from this analysis were higher in all cases except for arsenic. In comparison to other sludge types and sludge from earlier analysis from GWWTP it is not clear that one of the analysis results are more similar to these result, which makes it hard to see which analysis method that could be most relevant to compare with. The different results mainly indicate that it is important to make many analyses and many samplings. It is not enough to just use one result to judge the sludge and draw conclusions about its fate.

12.1.3 The sludge quality

This chapter describes the quality of sludge from Glen Valley WWTP in terms of nutrient value, heavy metal content, physiochemical parameters and pathogen content. The quality of the different sludge samples will be compared to each other, but they will also be compared with other fertilizers, other sludge types and also legislation.

Nutrient value

The nutrient value of the sludge from GWWTP will be discussed in terms of the different sludge types at the plant, in comparison to other fertilizers and in comparison to sludge from other treatment plants.

Different sludge types at GWWTP

The result of the sludge analysis indicates that the nutrient value of the sludge differs along the different treatment processes at GWWTP. The nutrient content seen in Table 10.1 shows that the secondary sludge has the highest nutrient value related to TS of the sampled sludge types for all measured nutrients, except for calcium. The fact that the secondary sludge shows higher contents of nutrients than the primary sludge agrees with Naturvårdsverket (2008), saying that nutrients are more likely to be removed with the secondary sludge than the primary sludge, due to their different treatment strategies.

The result also showed that the wet sludge types (primary and secondary sludge) in all cases had a higher nutrient content per TS than the dry sludge types. The explanation for this could be that some of the nutrients from the wastewater and sludge treatment processes follow the liquid effluent stream or that some of the nitrogen volatizes to gaseous form during the treatment processes of the sludge. This occurs for example when ammonium volatilizes to gaseous ammonia in contact with air.

It can also be seen that there is no great difference in nutrient content between the three dry sludge types. It can therefore be assumed that the time of storing may not have an effect on the nutrient value. There is though a small difference in the result. The analyses show that potassium is in lower concentrations for the old and older than the fresh dry sludge. This follows the theory stated by Ngole *et al.* (2006) saying that the storing time of dry sludge and the concentration of nutrients can be related. It is stated in the study that the longer the dry sludge has been stored, the lower will the concentration of nutrients be.

Comparison to other fertilizers

When comparing the nutrient content in the sludge from GWWTP with other fertilizers as in Table 11.1, it shows that the nutrient value differs between the different types of fertilizer. The dry sludge from Glen Valley wastewater treatment plant indicates a relatively low nutrient value in comparison to the artificial fertilizers and digestate. Cow manure and blackwater has however more similar nutrient content to sludge from GWWTP, but with a tendency to higher nutrient value in the cow manure and blackwater. This result could be explained by many reasons. The nutrients in both cow manure, blackwater and sewage sludge is mainly derived from urine and feces. However, the nutrients that are separated to sewage sludge is firstly diluted with other wastewater streams which in comparison to cow manure and blackwater can be harder to separate in conventional WWTPs to a fertilizer product. Some of the nutrients in the incoming wastewater to the treatment plant will thus end up in the effluent stream instead of in the sludge. Cow manure and blackwater could therefore likely have a higher nutrient value than sewage sludge.

The nutrient content in fertilizers depends on a lot of different factors, like treatment, handling and sources etc. The content in non-artificial fertilizers can therefore differ in different countries where humans and animals have different diets. What must be remembered is thus that the chosen fertilizers to compare the sludge from GWWTP with are just examples on how the nutrient distribution can look like.

The artificial fertilizers on the other hand are synthetically produced to contain a required content of nutrients, which differs for different crop demands. It is therefore hard to relate the sludge to the artificial fertilizer alternative more than saying that this selected artificial fertilizer has a much higher nutrient value than the sewage sludge from Glen Valley wastewater treatment plant. The artificial fertilizer would in most cases be cheaper to transport and spread on the fields since the total weight per hectare could be lower than for nutrient poor sludge. The metal content per hectare would also be lower, which can be seen in the comparison in Table 11.4 with the unit g metal/kg P.

Comparison with sludge from other WWTPs
From the comparative analysis in chapter 11 it can be seen that the nutrient from Glen Valley wastewater treatment plant generally shows lower nutrient content in comparison to the sludge types from other WWTPs.

A reason for the lower phosphorous value result in the sludge from GWWTP could probably be due to the differences in treatment processes at the plants. At GWWTP there is no treatment process to remove phosphorous from the wastewater to the sludge. The phosphorous is assumed to be removed in the maturation ponds and can therefore not be recovered in the sludge. This is however not the case for the two Swedish treatment plants from the comparison. At Sjölunda WWTP chemical precipitation is used and at Öresundsverket WWTP enhanced biological phosphorous removal is used. A higher phosphorous content can thus be seen in these sludge types.

The nitrogen content in the different sludge types is more similar and that could probably be explained by the fact that the processes in the different treatment plants are quite similar regarding nitrogen separation. However, the nitrogen content in the studies at GWWTP from 2006 is higher than in this study from 2015. One difference is that in 2006 the sludge drying beds were in use and that 2015 the new sludge treatment plant is in use. There could also be a lot of other reasons explaining this difference, like how the digestion of the sludge was made, how the drying procedure was done and how the incoming wastewater looked like then and now. Analytical faults or the fact that only one sampling was made cannot either be ignored.

The potassium content is as well as nitrogen also quite similar between the different sludge types in this comparison. This could be explained by Ngole *et al.* (2006) saying that potassium is more likely to be separated to the liquid stream than to the sludge. It is therefore hard to separate potassium to the solid phase, independent on the treatment processes used.

The heavy metal content
The metal content in the sludge from GWWTP will be discussed in terms of the different sludge types at the plant, in comparison to other fertilizers and in comparison to sludge from other treatment plants.

Different sludge types at GWWTP
Differences in metal concentrations can be seen both between the dry (fresh, old and older) and wet (primary and secondary) types of sludge, but also between the different types internally. From both analysis B and S it can be seen that the primary sludge has the highest heavy metal content and the sludge with the lowest content of heavy metals differs for the different analyses. Analysis S shows that the secondary sludge has the lowest heavy metal value whereas analysis B is pointing on the fresh dry sludge. The different analyses give generally very different results for all the metals and the reason for this could for example be due to differences in method of digestion during the analysis procedure for the solid samples or other sources of errors during the laboratory trials.

According to the results in this study, the primary (anaerobic) sludge has in most of the cases higher concentrations of heavy metals in comparison to the secondary (aerobic) sludge. According to Oliver

& Cosgrove (1974), the heavy metals in insoluble form or adsorbed to particles are most likely to be separated in the primary treatment to the primary sludge, whilst heavy metals appearing in soluble form are mostly removed in the secondary treatment step to the secondary sludge. If it is assumed that the incoming wastewater to Glen Valley WWTP contains metals in both soluble, insoluble form and adsorbed to particles, it can be seen that most of the incoming metals therefore are in the insoluble form. According to this study, the secondary sludge is more favorable to use as fertilizer than the primary sludge, in terms of metal content.

The differences in heavy metal concentration between the different types of dry sludge are more unclear. According to analysis S the fresh sludge has the lowest heavy metal value whereas in analysis B, the oldest sludge has the lowest heavy metal content. It is not known if the old dry sludge is derived from the new sludge treatment facility started in 2009 and the storing time is not known. Therefore no deeper analysis can be made in order to determine reasons for differences in heavy metal content for the dry sludge types old and older.

Comparison to other fertilizers
From Table 11.4 it can be seen that the dry sludge from GWWTP in almost all cases has the highest heavy metal content in relation to the phosphorous content and in comparison to the selected fertilizer options; artificial fertilizer, co-digestate, cow manure and blackwater. This is the case for both analysis B and S.

In comparison to the other fertilizer options, sewage sludge is derived from wastewater which includes both domestic and industrial discharge. This means that the quality of sludge is dependent on the wastewater characteristics and thereby the influence from sources upstream in the sewage system. Industrial activities are of great importance. For artificial fertilizers, the metal content depends on the type of bedrock it is extracted from and how much treatment that has been done. The metal content in the manure is dependent on the food to the animals and it could also be the bedrock that the crops for the feeding are planted on. The metal content in blackwater is dependent on the household and food products approved in the country and also on the diet of the population.

Comparison to sludge from other WWTPs
When comparing the heavy metal content in sludge from Glen Valley WWTP with the sludge types from other plants, it is hard to determine and asses clear differences. A clear trend in sludge quality from different treatment processes and countries cannot be seen. However, the impact of stormwater could be interesting to analyze when looking at the comparison between sludge from different plants. In Sweden a great part of the sewer system consists of combined pipe systems, allowing stormwater and runoff from roads with influence from urban activities and traffic to enter the pipe system together with wastewater. This water could be heavily polluted and might contain high concentrations of heavy metals. In comparison to Sweden, the sewer system in Botswana deals almost exclusively with wastewater without stormwater and this could impact the content of heavy metals in the sludge. Other factors affecting the differences in sludge quality in Sweden and Botswana could be the amount and types of industries and other urban businesses and the time that regulations have existed and developed, see chapter 14.3.

Legislation
By comparing the sludge quality with the regulations in South Africa, Sweden and EU, an idea of the hazardous content of the sludge can be given. This is though only true if the limits have been set up according to what values that do not result in an accumulation in the crops.

In this study arsenic, copper, lead and zinc exceed some of the mentioned limits. The question where these metals can origin from is not easy to answer, since the industries in Gaborone are, according to this study's knowledge, no heavy polluters. In chapter 4.3 different sources to these metals are listed.

The limits in EU for metal content in sludge are very high and have been criticized from a lot of member states, since they are from 1987 and more research about the hazardous effects of heavy metals have been done since then. That means that it is not a guarantee that if the sludge do not exceed these limits, it is totally safe to use.

New studies show different conclusions about the use of sludge in agriculture and it is hard to examine exactly how crops and consumers of food produced on a sludge spread field are impacted of it. One reason for that could be that there are a lot of factors that the metal uptake depends on, mentioned in the literature study. It is not possible to give one answer for all sludge types spread on all land types with all crops types. It is different depending on what the sludge looks like, how the properties of the soil in the field are and what type of crop that is being grown.

Physiochemical parameters
The physiochemical parameters in the sludge from GWWTP will be discussed only in terms of the different sludge types at the plant since these parameters have not been in focus in this study and also differ among the processes that different plants are using.

Different sludge types at GWWTP
From the result it was seen that the value for TS was relatively low for the primary and secondary sludge in comparison to the three dry sludge types, see Table 10.1. This trend can be seen for all sludge types except for the oldest dry sludge which has a considerably lower value of TS than the others. This deviation is not probable and could be due to an error within the measurements. This trend in TS seems however to be reasonable having in mind the consistence of the different types of sludge at sampling. The VS analysis shows that the values are quite similar for all types of sludge except for the older dry sludge. This again could be due to an error within the measurements or during sampling.

The measurement of pH was only made for the primary and secondary sludge since no available measuring instrument was found for pH analysis of dry sludge. Since pH of the dry sludge is of great importance for the use in agriculture, it would be useful to know the pH for these types of sludge as well. Measurements of pH must also be done more often in order to determine variations and external influences. What can be seen from the performed pH analysis is though that the pH for the secondary sludge was comparable low to come from an aerobic sludge treatment. This could maybe depend on an inaccurate pH-meter or measurement errors. The pH was also low in the primary sludge which as well could be a result of an inaccurate pH-meter. It could also be a result of an uneven balance between hydrolysis and methanogesis in the anaerobic digestion, where the hydrolysis is dominating since the microorganisms active in that process can live at lower pH.

Pathogens
Pathogens have not been measured in this study. The assumption is however that the UV-radiation from the sun when the sludge is stored in piles is enough to eradicate the pathogenic activity if the sludge is stored long enough.

12.1.4 Possible improvements of the sludge quality

There are several aspects within the maintenance or with the processes used at the treatment plant that could possibly affect the quality of the sludge. For example, there were problems with the maintenance of the air grit chamber during a period around the time of the sampling. This source of error could possibly influence the quality of sludge. An increased amount of sand or bigger particles in the primary settling tank may contribute to increased adsorption surface for heavy metals. This could therefore be a part of the explanation for the higher concentration of heavy metals in the primary sludge.

From the visit at GWWTP and the results of the physiochemical parameters of the sludge it could be seen that some important parameters for operation of the anaerobic digester was not met. During the time of the sampling, the temperature was too low and there were no mixing of the sludge in the digester. With increased control and better management of the digester the mineralization process would possibly be more effective.

Another influencing factor for the sludge quality may be the method for phosphorous removal. If the phosphorous removal is based on chemical precipitation, phosphorous in the wastewater will bind to the added chemical agents and eventually sink to the bottom of the settling basin and be removed as sludge. One drawback associated with the use of chemical agents for phosphorous removal could though be that the agents often contain heavy metals and decrease the availability of the nutrients for the plants. When enhanced biological phosphorous removal is used, microorganisms with extra stored phosphorous in their bodies will eventually be removed as sludge. Glen Valley wastewater treatment plant does not use neither chemical precipitation nor biological phosphorous removal at the moment, which leads to that a relatively small amount of phosphorous is separated to the sludge.

Finally it can be said that the secondary sludge shows positive properties regarding both nutrient and heavy metal content in terms of fertilizer potential since this sludge type had the highest nutrient value and the lowest metal content in comparison to the other sludge types analyzed in this study.

12.2 The management and use of sludge

Even if there is a current strategy for the sludge management of produced sludge at GWWTP, the management strategy could be optimized in order to increase the sludge's potential as fertilizer. Below follows a brief discussion about the current status and challenges with the sludge management and use in Botswana, as well as future strategies. Documentation, storage, quality control and impact of sludge use in agriculture will be discussed.

Documentation

The documentation of sludge amounts produced at the plant could be developed so that the capacity of the sludge treatment plant could be known. With this information, the sludge treatment plant could also be optimized and well adapted to the demands from the customers buying the sludge. One goal might be to have a stable and continuous sludge production, to ensure that customers will be able to buy it all year around.

Strategy for sludge storage

Right after the sludge treatment process, sludge is spread out in no specific order in piles. Here it would be beneficial to have a system where the sludge is placed in order after time. By knowing how long the sludge has been stored, it would be possible to determine the hygienization grade and pathogenic status of the sludge. This is desirable to ensure and prove that bacteria have died off and that the sludge has been exposed for UV radiation during a sufficient time and that it is safe to use in terms of pathogenic content.

Another advantage with storing the sludge in piles organized after time is that it would be possible to prevent sludge with inadequate quality to be sold. This sludge could be removed and later used for other purposes than fertilization.

By not only organizing the sludge after time but also quality, it could be possible to evaluate the efficiency of the sludge production. By doing this, the staff at the plant can know when the sludge is produced and relate it to the function of the plant. This information will be helpful for the optimization and development of the plant.

Sludge quality control

At the moment there is no continuous quality analysis of the sludge produced at Glen Valley wastewater treatment plant. This not only makes it impossible for customers to know what is in the sludge they buy, but also for the staff at the treatment plant to be able to analyze and improve the quality of the sludge and operation of the sludge plant. Continuous analysis is important in order to prevent that compounds hazardous in both environmental and health aspects are spread on farmland.

An important step could therefore be to set up a national legislation for the sludge quality when using sludge as fertilizer. Routines for continuous sludge quality analysis could also be set up, saying that the sludge should be analyzed both in terms of nutrients and heavy metals, micropollutants and other trace elements.

Analyze and control of the impact of sludge use in agriculture

In order to analyze the impact of the use of sludge in agriculture, it would be preferable to analyze and document the status of the fields where the sludge is spread. Important aspects could be the amount of sludge spread, the quality of sludge spread, the quality of the soil etc. This could help to track deviations and find possible reasons to problems. If there would be a register over both sludge and soil quality on the fields where the sludge is spread, it would be easier to see what possible benefits and drawbacks there can be with the spreading.

In order to make the sludge a commercial product, a suggestion could be to give the customer some kind of receipt telling that the bought sludge is of good quality. It could be some kind of certification system or a statement from the laboratory staff. That could make the product more reliable and the price could possibly be higher for the sludge of good quality that is sold.

Strategy for the fate of sludge

There is a lot of sludge stored at GWWTP that is not being sold. There is no known plan of how this stored sludge should be handled and what the fate of it should be. Today there is no problem with storage area and there is plenty of space at the wastewater treatment plant site that is still not in use. But the problem with just storing the sludge at the plant is that the nutrients in the sludge could be drained to the environment where they can cause eutrophication and other environmental problems. The nutrients in the sludge should be recycled and used for a purpose in order to achieve sustainable development. A suggestion could be to use the drying beds to take care of the nutrient rich drained water. By placing the sludge in piles in the squared beds, it could be easier to organize the sludge according to production time.

General
In 2009 the treatment process for the sludge was upgraded with the vision to prioritize the sludge handling more. But the sludge treatment plant needs to be maintained in order to work properly and guarantee a sludge quality as good as possible all the time. The maintenance of the sludge plant could be prioritized higher than it is at the moment.

Even if the wastewater treatment plant has started to prioritize the sludge handling, it is still other challenges that take focus from the sludge. For example, there are problems with sand in the wastewater which is not separated in the air grit chamber that disturb the further treatment processes. There are also problems with leaking of untreated wastewater at the plant. In the water sector the largest challenge is the water scarcity and to provide safe drinking water. In the pipe networks there are problems with fats and grease and blockings. This is not a reason to disregard the sludge, but could be raised to policy makers in Botswana in order to relocate money to the wastewater sector.

12.3 The work with sludge quality improvements

The Trade Effluent Agreement in Botswana aims to regulate and control the industrial wastewater discharge to the public sewer systems in Botswana so that it meets the set quality standards and does not cause harm to the sewer network or to the public health. So far the work with source tracking has proceeded well in Botswana considering the short time that the work has been going on. There is a clear strategy for the work with source tracking and tasks are divided between different departments and authorities. The goal with the TEA is clearly stated and there are visions to reach effluent quality below the discharge limits from Glen Valley wastewater treatment plant.

The work with the TEA has just started and it is too early to see any result of the wastewater quality from the work. A challenge has thus been seen regarding the interest from industries and to get industries signed to the agreement. The incitements to join the agreement could be higher or the work with involving industries could be raised.

In terms of regulations for the industrial wastewater discharge to the sewer system, the Swedish National water regulation in Sweden and the Trade effluent agreement in Botswana are quite similar in terms of the responsibilities and obligations for the involved parts. A significant difference is though the discharge limits for the industries in to the sewer network. Trade effluent agreement allows higher concentrations of heavy metals than the Swedish National water regulation. The reason for this could be due to different approaches to the source tracking work or the fact that the countries have worked with source tracking for different length of time. In Botswana, the work with source tracking is relatively new and the focus is put on preventing discharge of wastewater to the sewer system that is of harmful characteristics for the sewer system. In Sweden on the other hand the work with source tracking has proceeded for many years and the focus is more put on improving the sludge quality for agricultural purposes. Different elements can also be in focus in the source tracking work for the different countries.

The link between sludge quality and source tracking could also be stronger. The source tracking in Botswana is mainly focused on the effluent water stream from GWWTP and that the discharged wastewater to the sewer system does not harm the pipe system. The focus on the sludge quality improvement is thus not that clear. However, the explanation for this could be that the regulation for effluent water released to the recipients is very strict, in comparison to the limits for sludge quality, which is absent. The poor focus on sludge quality could also be due to that the improvement of the sewer system is prioritized. The link between sludge quality improvements and source tracking can thus be improved by analyzing the sludge quality and finding the most critical elements to focus on.

These elements can then be tracked upstream in order to find potentials for preventing it to enter the wastewater stream. This would make the work with source tracking more focused on making the sludge into a good fertilizer.

It is seen that there are many current and future challenges for the water and wastewater companies, as well as the wastewater treatment plants in Botswana. Hence, it may be difficult to motivate the focus on sludge quality improvements. However there could be stronger incitements for these companies to improve the sludge quality. For example, the Swedish wastewater treatment plants can voluntarily join the certification system REVAQ and strive to get their sludge approved to be used as fertilizer. The sludge is being certificated and is accepted to be used as fertilizer, a much cheaper way to dispose the sludge than other alternatives. A suggestion could be to implement a similar system in Botswana.

12.4 Broader discussion

The fate of sludge

The question about sludge use has been discussed in many years and the large question is: What will happen with the sludge produced? This question is often raised due to lack of accessible land, expensive transportation options and quality reasons. Since sewage sludge contains both hazardous and useful constituents for the environment, the question does not need to be raised in that manner but could instead be: What to change in the treatment or in the usage? Below some options to recycle nutrients are discussed.

Pit latrine sludge as fertilizer

As Botswana and especially Gaborone suffer from water scarcity and as the sludge from Glen Valley wastewater treatment plant contains hazardous compounds and low concentration of nutrients, it would be interesting to investigate the use of sludge from pit latrines as fertilizer and keep the pit latrines instead of connecting more households to the water-based public sewer system.

A large part of the town is not connected to the sewer system and the pit latrines only contain urine, feces and toilet paper. The nutrients are more concentrated in the sludge from pit latrines since they are not diluted with flushing water, discharged water from industries or drained water into the pipes. This sludge also contain less heavy metals and other hazardous compounds due to that it is not diluted with industrial wastewater.

Another advantage by using this sludge as fertilizer is that it could go directly from the pit latrines to the fields where it is used as fertilizer. However it needs to be treated for removal of pathogens first. There could of course be residuals from pharmaceuticals and an investigation over the quality is needed before any further conclusions can be made.

Instead of continuing to connecting water toilet facilities in different areas in the city to the sewer network it could be an idea to implement fresh, user-friendly and easy emptied pit latrines that can increase the possibilities to recycle nutrients from the city to the farmland. Then the drinking water can be used for better purposes than for transport of feces and urine and the WUC does not need to put more money into maintaining pipes and buying new manhole covers.

Wastewater treatment

The treatment plants are commonly not designed with the aim to produce nutrients, but to treat wastewater. However, there are solutions that can reach both goals. The activated sludge process is efficient in removing carbon and nitrogen, but it is then partly lost to the atmosphere in forms as carbon dioxide and nitrogen gas. These nutrients could be utilized as fertilizer when methods like filtration could be used. In membrane filtration, particles and ions are separated with very small space needed in comparison to an activated sludge process. Anaerobic treatment is interesting since only some carbon is consumed as carbon dioxide and the nitrogen is being mineralized and transformed to more accessible forms for the plants. If the water content is relatively low, it could be an idea to use the wastewater after an anaerobic digestion process as fertilizer. These solutions are not economically defendable in the short terms, but when treatment plants need to be re-built or expand, it could be interesting to look at these alternatives.

13 Conclusion

The quality of sludge from Glen Valley wastewater treatment plant has been examined and analyzed in terms of fertilizer potential. Possible improvements for increasing the sludge quality have also been discussed. Following conclusions can be made about the current fertilizer potential:

- In comparison to selected examples of fertilizers and other sludge types, the sampled sludge from GWWTP indicates a relatively low nutrient value. The heavy metal content in the sludge varies depending on analysis method used but in a worst case scenario, content of arsenic, copper, lead and zinc in the sludge does not meet the South African limits for sludge use in agriculture. From the results of this thesis it can also be seen that the secondary sludge from GWWTP indicates lower heavy metal content than the primary sludge.

There are however several actions that could be made to increase the fertilizer potential of the sludge at GWWTP. These actions are concluded below.

- A treatment process optimized for phosphorous removal, e.g. Chemical precipitation or enhanced biological phosphorous removal may increase the phosphorous content in sludge.

- The treatment process in the WWTP seems to have an influence on the sludge quality, both in terms of nutrient and heavy metal content. Lower heavy metal and higher nutrient content in the sludge may therefore be gained if only using the secondary sludge from GWWTP as fertilizer.

- A more nitrogen-rich sludge can be obtained if the sludge is kept in a closed storage instead of open air. This with reservation for methane gas production and a sludge product with more water and larger volume.

- The work with source tracking in Botswana may most likely contribute to a reduction of the heavy metal content in the sludge. However, more emphasizes must be put on getting industries to join the Trade Effluent agreement and in the future lower the limits according to the local problems seen.

Overall, the result from only one sampling occasion is not enough to estimate the quality of the sewage sludge. More continuous and frequent laboratory analysis of the sludge from GWWTP is needed to determine the fertilizer potential. This may also contribute to better operational prerequisites of the plant, but also a better assurance to the customers on the sludge status.

The analysis method is also of great importance for the sludge quality results. The choice of the analysis method must therefore be reviewed for future sludge analyses.

14 Further recommendations

Based on the conclusions from this thesis, this chapter will present further recommendations for the work with sludge quality improvements and fertilizer potential in Gaborone. Below follows suggestions of further work within sludge quality analysis, sludge quality improvements, source tracking, and sludge management followed by general recommendations.

Quality analysis
More continuous and frequent laboratory analysis of the sludge from Glen Valley wastewater treatment plant must be performed in order to set the actual potential as fertilizer. By doing this, seasonal variations in sludge quality may be seen and the operation of the plant could also be analyzed. If more samples are collected at the sampling occasion, the ranges and variations in the quality could be examined.

Further investigations could also be done of the method for heavy metal analyses. From the result of this thesis it can be seen that the heavy metal content in the sludge varies depending on the method used. Therefore, a more detailed analysis of the chosen methods must be done to ensure the reliability of the results.

Except from analyzing nutrient and heavy metal content in the sludge, contents of hazardous compounds like pathogens and micropollutants should also be investigated.

Improvements of the fertilizer potential in sludge from GWWTP
Further investigation can also be done about improvements for the sludge quality and thereby also the fertilizer potential. Following alternatives could be investigated: Introduce an optimized treatment step for phosphorous removal, keep the treated dry sludge in a closed storage and continue the work with source tracking but get more industries joining TEA.

The differences between the primary and secondary sludge in terms of fertilizer potential could however also be further investigated. This could increase the possibilities to be able to only use the most harmless sludge for fertilizer purposes.

The incitements of improving the sludge quality could possibly also be improved by national regulations for sludge quality in agricultural purposes.

Source tracking
The link between sludge quality and source tracking could be improved. When analyzing the sludge quality, the most hazardous and critical elements can be identified and tracked to sources upstream the treatment plant. The work with source tracking could by doing this be an efficient way to reduce the hazardous content in sludge. Further recommendations are therefore to identify the most critical element in the sludge and track it.

The work with source tracking could also be facilitated if the quality of wastewater were analyzed at different locations along the wastewater pipe network but also at the industries. This is also an alternative which could facilitate the work with source tracking.

The industry's approach to the Trade Effluent agreement could also be further investigated in order to see how the agreement is received from the WUC. By having open conversation with the industries, the knowledge and understanding of the consequences of discharging hazardous compounds to the wastewater pipe network could also be increased.

Sludge management

Further recommendation is to have clear documentation of both quality and the quantity of sludge produced at Glen Valley wastewater treatment plant. This could be rewarding information for both the staff at the plant, but also for the customers buying the sludge.

A clear policy or plan could increase the security for the sludge management at Glen Valley wastewater treatment plant. The policy could both work as a guiding document for the staff, but could also be an insurance for the customers that the sludge has been handled in the right manner.

General

Increased financial support is also something that could be investigated. The sludge treatment and management system is possibly in need of increased economic resources to be able to develop. But as discussed in previous chapter, there are other challenges facing the WUC and therefore it could be hard to increase the financial support with a limited budget.

Another investigation that can be done is the use of fecal pit latrine-sludge as fertilizer. Instead of adding the fecal sludge to the incoming wastewater stream to the wastewater treatment plant, it could instead be treated separately without dilution and therefore become an own fertilizer product.

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Appendix I – Classification of sludge in South Africa

Sewage sludge in Botswana and South Africa is classified within four types; type A, B, C and D. The classification is based on the potential to cause odor nuisances and fly breeding but also the potential to transmit pathogenic organisms to humans and the environment. Type A and B sludge has high content of pathogenic organisms whereas type C and D sludge should have much higher quality and must therefore be certified in order to comply with certain quality requirements. The hygienic quality for type C and D sludge is based on the presence of pathogen indicators Ascaris ova, Salmonella organisms and fecal coliforms (Water Research Commission, 1997).

The different sludge types can be used for agricultural purposes within specific prerequisites. Type D sludge can be used for agricultural purposes without any restrictions but up to an annual spread of 8 ton/ha. An additional rule for this sludge to be used for agricultural purposes is that it must contain metal and inorganic contents below the maximum limits for sewage sludge. Type A and C sludge can be utilized as fertilizer or soil amendment under certain restrictions, and the sludge producer is responsible for the safe handling and disposal of the sludge.

Appendix II –Trade Effluent Agreement

Table IIa. Trade Effluent Agreement Structure (Water Utilities Corporation, 2012).

Activity	**Department/ Unit**	**Profile**	**Resources**
1. Registration	SHEQ	- Identify industries - Signing of the document - Give notification update on progress of signing to relevant departments - Request for inclusion of pre-treatment in structural drawings - Request for Environmental management plan (EMP) for new connections	Manpower Mode of transport
2. Sampling	Operations	- Identify sampling points - Create sampling schedule (but ad-hoc to customer) - Reading of flow meters - Sample the industries	Mode of transport Manpower
3. Analysis	Water quality	- Receive samples - Analyze samples - Produce report of analysis (including recommendations) and communicate it	FOG Analyzer
4. Reporting	Operation	- Adress non conformities - Determine invoicing format - To ensure reports reach credit control - To ensure reports reach industries	Mode of transport
5. Invoicing	Credit control	- Receive data of industries from SHEQ and Operations - Bill the customers - Disconnections and reconnection - Give feedback on payment	-
6. Compliance & policing	SHEQ	- Receive EMP from industries - Conduct random visits of industries - Ensure compliance	Mode of transport Manpower
7. Review and verification	TEA task team	- To hold review meetings	-

Table IIb. Acceptable industrial effluent discharge limits into the public sewer (Water Utilities Corporation, 2012)

Category		Parameter	Unit	Acceptable	Maximum
Physical	1	Temperatureat point of entry	°C	0-43	43
	2	Electrical Conductivity	mS/m	-	500
	3	pH (at 25°C)	-	6.0-9.5	9.5
	4	Suspended Solids	mg/l	500	1000
	5	Settleble solids (60 minutes)	ml/l	-	50
	6	Fats, Oils and Grease (FOG)	mg/l	100	250
	7	Caustic Alkalinity (as $CaCO_3$)	mg/l	-	2000
Chemical	1	Chemical Oxygen Demand (COD)	mg/l	1000	5000
	2	Phosphate (as P)	mg/l	-	30
	3	Ammonia (as N)	mg/l	-	100
	4	Chloride (as Cl)	mg/l	-	500
	5	Sodium (as Na)	mg/l	-	500
	6	Fluoride (as F)	mg/l	-	5.0
	7	Sulphates (as SO_4)	mg/l	500	1500
	8	Sulphide (as S)	mg/l	-	50
	9	Cyanide (as CN)	mg/l	-	20
	10	Phenols (as C_6H_5OH)	mg/l	-	50
	11	Sugar Starch	mg/l	-	500
	12	Total Dissolved Solids (at 105°C)	mg/l	-	4000
	13	Volatile Solvents	mg/l	-/I	Nil
Metals Gr 1	1	Iron (as Fe)	mg/l	-	20
	2	Manganese (as Mn)	mg/l	-	20
	3	Total Chronium (as Cr)	mg/l	-	10
	4	Silver (as Ag)	mg/l	-	20
	5	Zink (as Zn)	mg/l	-	20
	6	Nickel (as Ni)	mg/l	-	20
	7	Cobalt (as Co)	mg/l	-	20
	8	Titanium (as Ti)	mg/l	-	20
	9	Tungsten (as W)	mg/l	-	20
	10	Aluminium (as Al)	mg/l	-	20
		Total collective concentration of all metals in Group 1 shall not exceed 50 mg/l			

Metals Gr 2	1	Arsenic (as As)	mg/l	-	5
	2	Lead (as Pb)	mg/l	-	5
	3	Copper (as Cu)	mg/l	-	5
	4	Selenium (as Se)	mg/l	-	5
	5	Cadmium (as Cd)	mg/l	-	5
	6	Boron (as B)	mg/l	-	5
	7	Molybdenum (as Mo)	mg/l	-	5
		Total collective concentration of all metals in Group 2 shall not exceed 20 mg/l			