Metals in Sewage Sludge in the Eastern Cape

Minor Field Study

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Göteborg, Sweden 2002

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Preface

This study has been carried out within the framework of the Minor Field Studies (MFS) Scholarship Programme, which is funded by the Swedish International Development Cooperation Agency, Sida.

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ABSTRACT

Sewage sludge has long been considered a waste product, but with the realization of sustainable development the recycling and re-use of valuable nutrients contained in the sludge is becoming a key issue. The beneficial use of sludge is also receiving considerable attention because of the decline in available landfill. The problem with recycling nutrients from sewage sludge to agricultural soil is mainly due to the fact that sewage treatment plants often have difficulties in retaining the sludge unpolluted. Special attention has been paid to the presence of heavy metals in sewage sludge, partly because of their toxicity and partly because of their persistence in the environment.

A case study of the Easter Cape region in South Africa was carried out in this study where samples of sewage sludge were collected at three different wastewater treatment plants and analyzed on metal content. Three samples of Swedish sewage sludge was also included in the analysis. The samples where taken from the final sludge disposal at each treatment plant e.g. drying beds/lagoons. Heavy metal concentrations were determined by using ICP-MS (Inductively Couples plasma – Mass Spectroscopy) while metal fingerprinting took place with LA (Laser Ablation)-IPC-MS.

It is found that the sludge quality vary between the three treatment plants and between South Africa and Sweden. Dimbaza Sewage Treatment Works, despite the fact that it is located in the rural area outside a township, have a significant problem with heavy metal content compared to what was found in the sludge from Shornville Sewage Treatment Works and Zwelitsha Sewage Treatment Works. At Shornville Sewage Treatment Works, where the sewage sludge is known to be used as additional humus material on land and as natural fertilizer, levels of metals has been proven high enough for accumulating in the soil. It was concluded that Zwelitsha Sewage Treatment Works has the best sludge quality with regards to heavy metal content and is the plant that offers the most optimistic possibilities of sludge used as agricultural fertilizer or other land applications.

Key words:
sewage sludge, sludge treatment, wastewater treatment plant, metals, ICP-MS, LA-ICP-MS, soil fertilizer, South Africa

ACKNOWLEDGEMENTS

This master thesis is a result of hard work, time and effort, but the final outcome is not a product made by the authors only. Many people have contributed to the work and assisted the procedure in various ways. We would like to express our deepest gratitude to all people involved but especially acknowledge:

- **Prof. Gregory Morrison**, our supervisor and examiner at Chalmers University of Technology (Water Environment Transport), for initiating this project to us and guiding us through it. Your ideas and comments have been of great value and use.
- **Prof. Olalekan Fatoki**, our supervisor at University of Fort Hare (Department of Chemistry), for arranging our well being in South Africa and actively introducing us to academic and municipal expertise. Without your help it would certainly not have been possible to carry out our case study. Thank you so much for this!
- **Dr. James Adediran**, our dear neighbor and 'lab assistant' at University of Fort Hare (Department of Agronomy). Thank you for great smile and help in the lab, making sure our lab work proceeded smoothly.
- **Dr. Sebastien Rauch**, our lab supervisor at Chalmers University of Technology (Water Environment Transport), for your hours of help with our sample analysis. We are so grateful.
- **Dr. Remi Ogunfowukan**, at University of Fort Hare (Department of Chemistry), for being our housemate as well as showing us around campus and Alice. Sorry for converting the living room into an office, thank you for your patience. By the way, we are non-smokers now!
- **MSc. Eric Zinn**, solid waste management consultant at SWECO VBB VIAK AB, for giving advice regarding plans and preparations as well as establishing contacts in South Africa. Thank you for your company and hospitality in East London. Without you the potholes would probably have killed us!

Further, we would like to thank the superb staff at

- **Department of Agriculture in Bisho**
- **Department of Engineering in Bisho**
- **Dimbaza Sewage Treatment Works**
- **Shornville Sewage Treatment Works**
- **Zwelitsha Sewage Treatment Works**
- **Department of Agronomy at University of Fort Hare**

To you we owe a lot. Your great attitudes and cooperation meant a lot for the smooth procedure of our work. We thank you for your time and effort in finding us documentation and answers to the many questions.

The case study was financed by **Sida** (Swedish International Cooperation Development Agency) and by the **CF** (Swedish Association of Graduate Engineers), which we finally want to acknowledge for believing in us and having faith in our project. We are very grateful for the experience that this MFS (Minor Field Study) has given us.

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1 INTODUCTION

Sewage sludge is produced in wastewater treatment plants as solids and liquids are separated through a number of processes (figure 1). Of the constituents removed by treatment, sludge is by far the largest in volume and its processing and disposal is perhaps the most complex problem facing the engineer in the field of wastewater treatment (Tchobanoglous and Burton, 1991). The problems of dealing with sludge are complex because;

- it is composed largely of the substances responsible for the offensive character of untreated wastewater,
- the portion of sludge produced from biological treatment requiring disposal is composed of the organic matter contained in the wastewater but in another form, which can also decompose and become repulsing and,
- only a small part of the sludge is solid matter.

With the problem of fast growing population and rapid urbanization the amount of sludge being produced is becoming a growing problem, concerning not only wastewater engineers. Sewage sludge has long been considered a waste product, but with the realization of sustainable development the recycling and re-use of valuable nutrients contained in the sludge is becoming a key issue (Lundin, 1999).

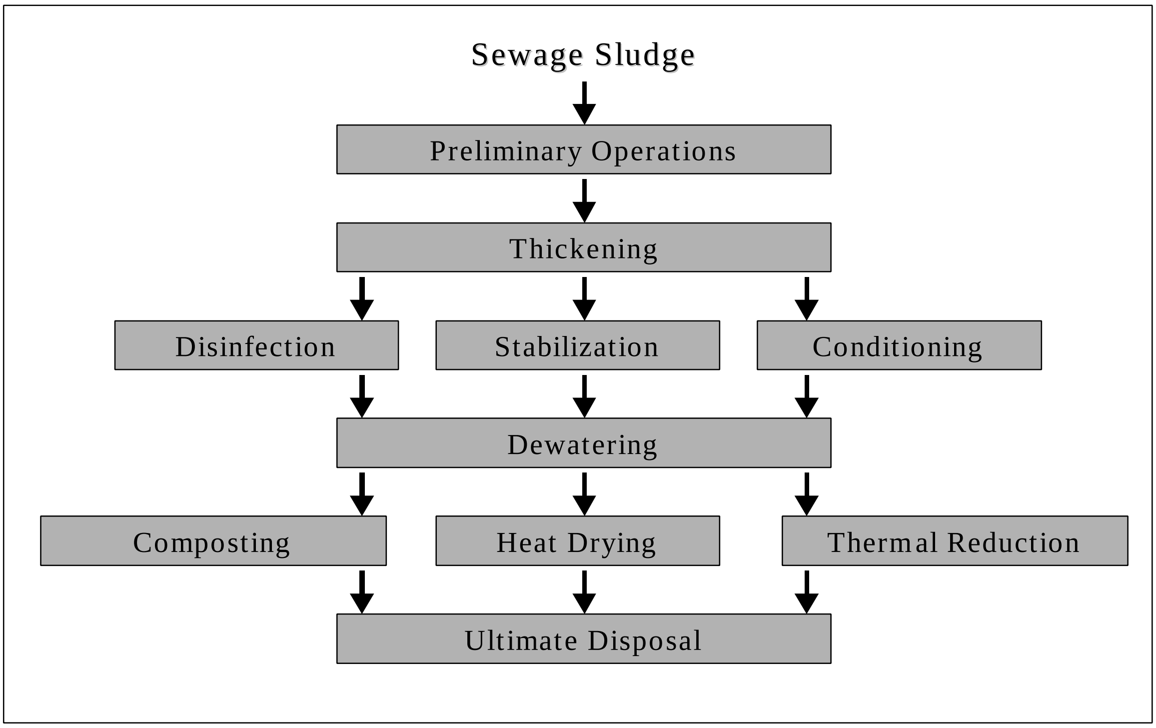

Figure 1. The steps of sewage sludge treatment.

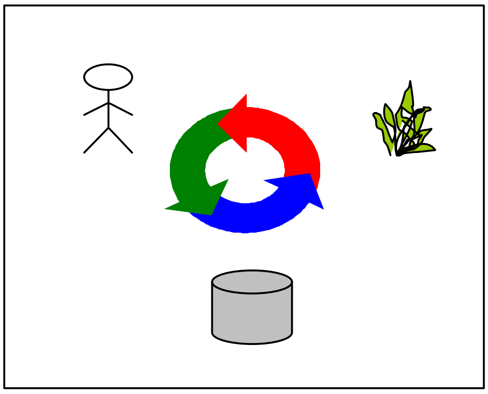

Figure 2. Recycling of nutrients in the environment.

Sewage sludge can be used as agricultural fertilizer both because of its enrichment in nutrients such as nitrogen and phosphorus and its high organic and structural content. Sludge also contains higher concentrations of easily available nitrogen (ammonium nitrogen) compared to manure (NVA). Land application of sewage sludge would thus be a sustainable practice as nutrients would be recycled in the environment (figure 2). The main reason for recycling phosphorus is the limited global resource of mineral phosphate. This nutrient is essential for plant growth, and a resource, which cannot be substituted. Phosphorus from rock is expected to last another 150 to 200 years (SEPA, 1995). Nitrogen is not a limited resource but the production of nitrogenous fertilizer demands significant quantities of energy and pollutes with air emitting substances such as carbon dioxide and nitrogen oxides (UNEP, 1996).

The problem with recycling nutrients from sewage sludge to agricultural soil is mainly due to the fact that sewage treatment plants often have difficulties in retaining the sludge unpolluted. Due to the sewage infrastructure in Sweden, persistent organic pollutants and metals from households, industry, stormwater and the water pipe system contribute significantly to the contamination of sludge and reduce its quality and possibilities for use as agricultural fertilizers (Lundin, 1999). Special attention has been paid to the presence of heavy metals in sewage sludge, partly because of their toxicity and partly because of their persistence in the environment (Ekvall, 1995).

The detrimental effects of heavy metals are well documented, but the actual effects of using sludge containing these metals have yet to be asserted. Several factors are currently being researched, e.g. availability, actual crop uptake, long-term effects on human health as well as other uncertainties (Zinn, 2000).

In Sweden only about 20% of the phosphorus and less than 5% of the nitrogen that leaves agriculture as plant and animal products are returned to agriculture (Granstedt, 1993 in Robért, 1995). Western societies seem to be stuck in a legislative and infrastructure trap regarding these issues. This can be prevented in developing countries by constructing sustainable infrastructure from the beginning.

1.1 OBEJECTIVES

The objectives for this master's thesis are the following (figure 3):

- Understand the different treatment processes used for sewage sludge
- Supply detailed information on treatment operations at wastewater treatment plants as well as for ultimate disposal opportunities for sewage sludge
- Carry out a case study of the Eastern Cape region in South Africa with the ambition to

- Collect sewage sludge from three different wastewater treatment plants in the study area
- Gather information related to sludge quality and disposal in the study area
- Analyze the metal content in the collected sludge, as well as in Swedish sludge with ICP-MS (Inductively Couples plasma – Mass Spectroscopy) and LA (Laser Ablation) techniques
- Compare the Swedish and South African sludge characteristics
- Investigate possible sustainable sludge use in the study area with special attention on the use of sludge as agricultural fertilizer based on analysis results

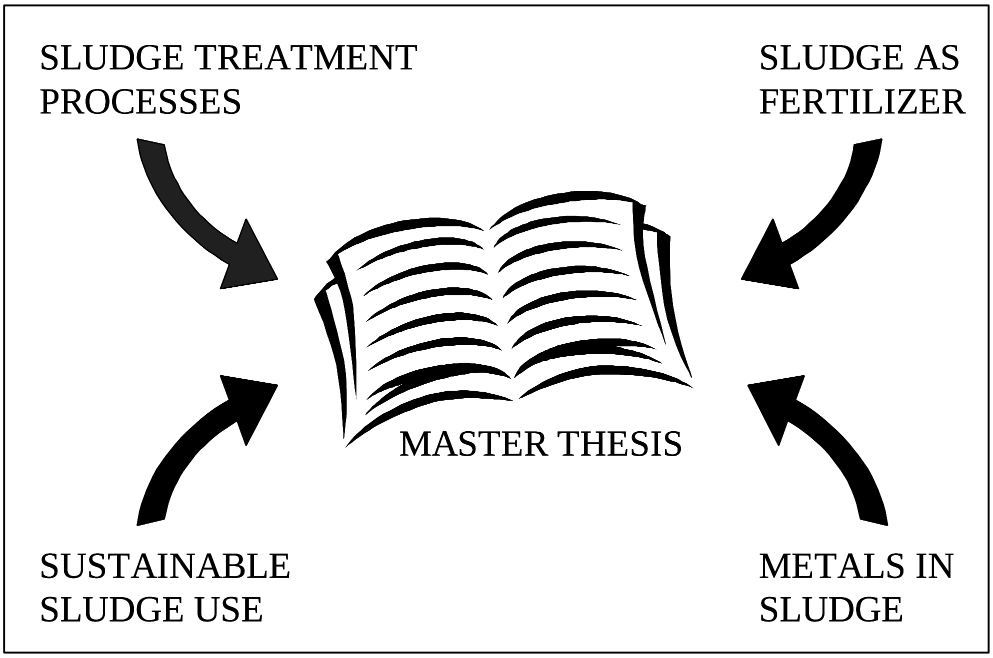

Figure 3. Objectives of the study.

1.2 METHODOLOGY

The study presented in this report was carried out both at Chalmers University of Technology (CTH) in Sweden and University of Fort Hare (UFH) in South Africa.

Practical preparations together with extended literature search and visits to sewage treatment plants started out in Sweden while the time spent at UFH focused on the case study. During the eight weeks in Africa many field trips were made with focus on visits to sewage treatment plants in order to collect sludge samples and retrieve detailed knowledge on the sludge cycle at each plant. Further information was gathered by a number of interviews with farmers that are currently using sludge as fertilizer on their land as well as with authorities; Department of Agriculture, Department of Water Affairs and Engineering. These were informative sources on sludge policies and regional land use and planning. At UFH additional interviews were made with expertise in the Faculty of Agriculture regarding soil issues of the area and Faculty of Chemistry of which the local study supervisor belongs.

The collected samples were taken to Sweden where further visits to sewage treatment plants were made as well as consulting expertise throughout the sample analysis. Report writing have been taking place throughout the case study period and finally completed at CTH after the analysis (figure 4).

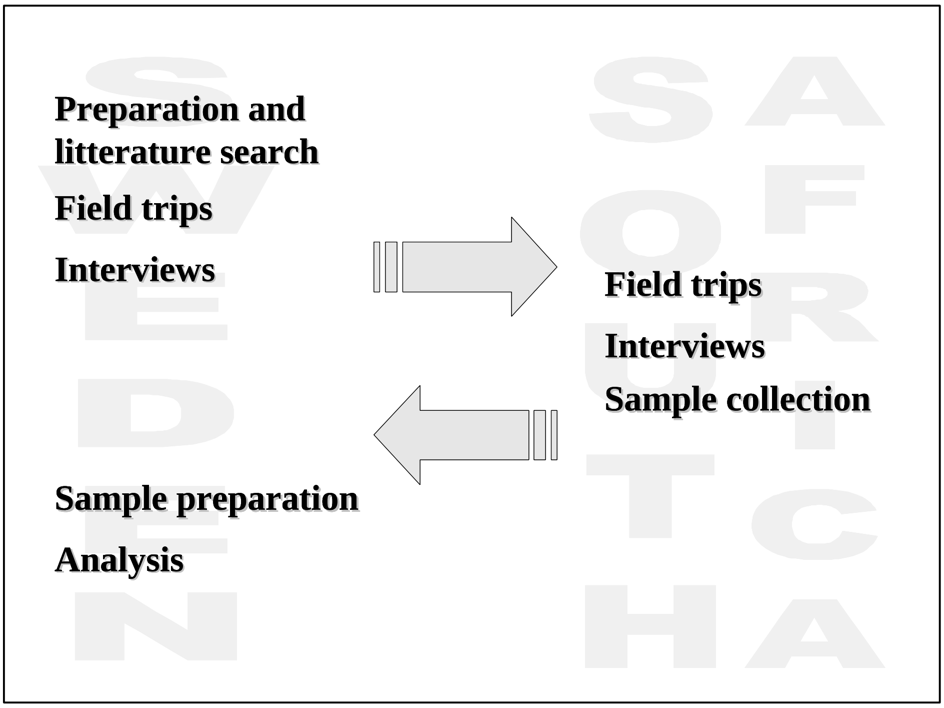

Figure 4. Methodology of the study.

2. SEWAGE SLUDGE SOURCES, QUANTITIES AND CHARACTERISATION

2.1 SOURCES

The sources of solids in a treatment plant vary according to the type of plant and method of operation. The principal sources of solids and sludge and the types generated are reported in table 1 (Tchobanoglous and Burton, 1991).

Table 1. Sources of sludge from a conventional wastewater treatment plant (Tchobanoglous and Burton, 1991)

Unit operation or process	Types of solids or sludge	Remarks
Screenings	Coarse solids	Coarse solids are removed by mechanical and hand-cleaned bar screens. In small plants, screening are often comminuted for removal in subsequent treatment units.
Grit removal	Grit and scum	Scum removal facilities are often omitted in grit removal facilities.
Preaeration	Grit and scum	In some plants, scum removal facilities are not provided in preaeration tanks. If the preaeration tanks are not preceded by grit removal facilities, grit deposition may occur in preaeration tanks.
Primary settling	Primary sludge and scum	Quantities of sludge and scum depend upon the nature of the collection system and whether industrial wastes are discharged to the system.
Biological treatment	Suspended solids	Suspended solids are produced by the biological conversion of BOD. Some form of thickening may be required to concentrate the waste sludge stream from biological treatment.
Secondary settling	Secondary sludge and scum	Provision for scum removal from secondary settling tank may be a requirement from the local environment protection agency.
Sludge-processing facilities	Sludge, compost and ashes	The characteristics of the end products depend on the characteristics of the sludge being treated and operations and processes used. Regulations for the disposal of residuals are becoming increasingly stringent.

The quality and nature of sludge depends on the characteristics of the wastewater and on the nature and efficiencies of the treatment processes (Donald *et al*, 1995). The characteristic of sludge also depends on whether it is biological or chemical as well as whether it is a primary or secondary sludge or a mixture of both (table 2). Many wastewater treatment plants mix the primary and secondary sludge for ease of disposal; however, subsequent treatments may thus be limited. The characteristic of sludge can further be described as physical, chemical and biological (see section 2.4 –2.6).

Table 2. Typical sewage sludge quantities before dewatering (Kiely, 1997).

Unit process	Dry solids, DS (%)	g DS/person/day
Primary settling tank	≈ 5	≈ 30
Primary settling tank (chemically entranced)	≈ 5	≈ 100
Secondary settling tank (activated sludge)	≈ 1	≈ 20
Secondary settling tank (Percolating filters)	≈ 2	≈ 20

The measurement of pH, alkalinity, and organic acid content is important in process control of anaerobic digestion. The content of heavy metals, pesticides, and hydrocarbons has to be determined when incineration and land application methods are considered. The energy (thermal) content of sludge is important where a thermal reduction process such as incineration is considered. Characteristics of sludge that affect its suitability for land application and beneficial use include organic content (usually measured as volatile solids), nutrients, pathogens, metals, and toxic organics. The fertilizer value of sludge, which should be evaluated where the sludge is to be used as a soil conditioner, is based primarily on the content of nitrogen, phosphorous, and potassium. Typical nutrient values of sludge as compared to commercial fertilizers are reported in table 3. In most land application systems, sludge provides sufficient nutrients for good plant growth. In some applications, the phosphorous and potassium content of wastewater sludge may be too low to satisfy specific plant uptake requirements. Trace elements in sludge are those inorganic chemical elements that, in very small quantities, can be essential or detrimental to plants and animals. The term "heavy metals" is used to denote several of the trace elements present in sludge. Concentrations of heavy metals may vary widely. For land application, sludge concentrations of heavy metals may limit the sludge application rate and the useful life of the application site (see section 12.3) (Tchobanoglous and Burton, 1991).

Table 3. Comparison of nutrients levels in commercial fertilizers and waste water sludge (Tchobanoglous and Burton, 1991).

	Nutrients [%]		
	Nitrogen	Phosphorus	Potassium
Fertilizers for typical agriculture use[1]	5	10	10
Typical values for stabilized wastewater sludge	3.3	2.3	0.3

[1] The concentration of nutrients may vary widely depending on soil and crop needs.

2.2 QUANTITIES

The quantity of solids entering the wastewater treatment plant daily may fluctuate over a wide range. Thus, rates of production and storage capacity at a plant are key issues. A limited quantity of solids may be stored temporarily in the sedimentation and aeration tanks. The storage capacity can be used to equalize short-term peak loads. Where digestion tanks with varying levels are used, their large storage capacity provides a substantial dampening effect on peak digested sludge loads (Tchobanoglous and Burton, 1991).

2.3 PRIMARY AND SECONDARY SLUDGE

First stage treatment of sludge have the objective to reduce the sludge volume by reducing the volume of water, while secondary stage sludge treatment is used primary to treat or stabilize the organic material in the sludge (Kiely, 1997) (Table 4).

Table 4 Sludge treatment processes.

Primary stage sludge treatment	*Secondary stage sludge treatment*
Thickening	Disinfection
Stabilization	Composting
Conditioning	Heat drying
Dewatering	Thermal heating

The most common unit process in wastewater treatment is primary sedimentation to remove settleable solids that can be thickened by gravity settling. The sludge consists of organic solids, grit, and inorganic fines (Kiely, 1997). It contains a sizeable fraction of the influent biological oxygen demand (BOD), and will become anaerobic within a few hours, and must be isolated to prevent nuisance problems (Donald *et al*, 1995). Because it contains organic matter, it is suitable for further anaerobic digestion. Downstream thickening is provided by picket fence thickening (or other), followed by stabilization and dewatering (Kiely, 1997).

Solids escaping primary settling are either solubilized or become entrained in the biomass during secondary treatment. Additional solids are generated by conversion of dissolved organics into cellular material. Secondary sludge is thus composed primary of biological solids (Donald *et al*, 1995). They are produced as waste sludge from secondary settling tanks, after secondary treatment process, which include activated sludge, percolating filters and variations of these unit processes. The lack of organic matter makes secondary sludge less suitable for anaerobic digestion (Kiely, 1997).

Mixed sludge are those from combined primary and secondary sludge. This is sometimes used so that the easily dewatered properties of primary sludge can be used to assist (in dewatering) the more difficult (to dewater) secondary sludge (Kiely, 1997).

Chemical sludge results when lime, aluminum or ferric salt, etc., are added to improve the suspended solids removal or to chemically precipitate phosphorus. Water treatment sludge is chemical sludge. While some chemicals may be beneficial for dewatering (lime), other inhibits dewatering (Kiely, 1997).

2.4 PHYSICAL CHARACTERISTICS OF SEWAGE SLUDGE

The operations and the processes used to reduce water and organic content of sludge render it suitable for final disposal or reuse. Water in sludge may be of the following types (Kiely, 1997):

- Free capillary water
- Bound water
- Intercellular water (adsorbed)
- Intracellular water (absorbed)

The free water is readily removed from sludge by gravity settling with or without chemicals. The bound water, in intercellular form, is also removable (in part) but requires the addition of polymers. The intercellular water is retained by the sludge by chemical bonding, which may be broken by the addition of polyelectrolytes, which cause a change in the electric charges. The intracellular bound water is only possible to remove if the sludge particle walls can be broken by either heating, freezing or electroinduced forces. As such, the free water and intercellular water is removed by mechanical dewatering processes (see chapter 7).

Sewage sludge and solids comprise of lumpy, flaky and colloidal solids interspersed with water (table 5). The more capillary and bound water there is, the more difficult it is to dewater (Kiely, 1997). Primary sludge is more granular in nature than secondary sludge and is generally more concentrated. The consistency of secondary sludge is dependent on treatment processes and more variable (Donald *et al,* 1995). See table 6 for the usual physical characteristics of sludge.

Table 5. Description of physical characteristics of sludge and solids.

Solids or sludge	Description
Screenings	Screenings include all types of organic and inorganic materials large enough to be removed on bar racks. The organic content varies, depending on the nature of the system and the season of the year.
Grit	Grit is usually made of the heavier inorganic solids that settle with relatively high velocities. Depending on the operation conditions, grit may also contain significant amounts of organic matter, especially fats and grease.
Scum/grease	Scum consists of the floatable materials skimmed from the surface of the primary and secondary settling tanks. Scum may contain grease, vegetable and mineral oils, animal fats, waxes, soaps, food wastes, vegetable and fruit skins, hair, paper and cotton, cigarette tips, plastic materials, condoms, grit particles, and similar materials.
Primary sludge	Sludge from primary settling tanks is usually gray and slimy and, in most cases, has an extremely offensive odor. Primary sludge can be readily digested under suitable conditions of operation.
Sludge from chemical precipitation	Sludge from chemical precipitation with metal salts is usually dark in color, though its surface may be red if contains much iron. Lime sludge is grayish brown. The odor of chemical sludge may be objectionable, but is not as bad as primary sludge. While chemical sludge is somewhat slimy, the hydrate of iron of aluminum in it makes it gelatinous. If the sludge is left in the tank, it undergoes decomposition similar to primary sludge, but at lower rate. Substantial quantities of gas may be given off and the sludge density increased by long residence times in storage.
Activated sludge	Activated sludge generally has brownish, flocculant appearance. If the color is dark, the sludge may be approaching a septic condition. If the color is lighter than usual, there may have been under aeration with a tendency for the solids to settle slowly. Sludge in god condition has an inoffensive “earthy” odor. The sludge tends to become septic rapidly and then has a disagreeable odor of putrefaction. Activated sludge will digest readily alone or when mixed with primary sludge.
Trickling-filter sludge	Humus sludge from trickling filters is brownish, flocculant, and relatively inoffensive when fresh. It generally undergoes decomposition more slowly than other undigested sludge. When tricking-filter sludge contains many worms, it may become inoffensive quickly. Trickling-filter sludge digests readily.
Digested sludge (aerobic)	Aerobically digested sludge is brown to dark brown and has a flocculant appearance. The odor of aerobically digested sludge is not offensive; it is often characterized as musty. Well-digested sludge dewaters easily on drying beds.
Digested sludge (anaerobic)	Anaerobically digested sludge is dark brown to black and contains exceptionally large quantities of gas. When thoroughly digested, it is not offensive, its odor being relatively faint and like that of hot tar, burnt rubber, or sealing wax. When drawn off onto porous beds in thin layers, the solids first are carried to the surface by the entrained gases, leaving a sheet of comparatively clear water. The water drains off rapidly and allows the solids to sink down slowly on to the bed. As the sludge dries, the gases escape, leaving a well-cracked surface with an odor resembling that of garden loam.
Composed sludge	Composed sludge is usually dark brown to black, but the color may vary if bulking agents such as recycled compost or wood chips have been used in the composting process. The odor of well-composed sludge is inoffensive and resembles that of commercial garden-type soil conditioners.
Septage	Sludge from septic tanks is black. Unless the sludge is well digested by long storage, it is offensive because of the hydrogen sulfide and other gases that give off. The sludge can be dried on porous beds if spread out in layers, but objectionable odors can be expected while it is draining unless it is well digested.

Table 6. Physical characteristics of sludge (Kiely, 1997).

Parameter	Primary sludge	Secondary sludge	Dewatered sludge
Dry solids (DS)	2-6%	0.5-2%	15-35%
Volatile solids (VS)	60-80%	50-70%	30-60%
Energy content (MJ/kg VS)	10-22	12-20	25-30
Particle size (90%)	< 200 µm	< 100 µm	< 100 µm

2.5 CHEMICAL CHARACTERISTICS OF SEWAGE SLUDGE

The volatile organic substances of the sewage sludge are either solid or liquid. If the water is totally removed the remaining organic volatile matter (ash) are known as dry solids (DS) (Kiely, 1997). The organic content of both primary and secondary sludge is about 70 percent (Donald *et al*, 1995). The organic volatile matter may be characterized by its calorific value. Table 7 shows the range of the values for sewage sludge (Kiely, 1997). The inorganic content of sewage sludge varies widely but is typically about (Kiely, 1997):

- Waste activated sludge: 20-35 percent DS
- Primary sludge: 30-45 percent DS

As described in earlier sections, sludge may be either biological or chemical or mixed. However, all will have distinctive chemical characteristics including (Kiely, 1997):

- Metals
- Polymers
- pH
- Alkalinity
- Nutrients
- Polychloridebromides (PCBs), Dioxins

Table 7. Range of typical chemical composition of sludge (Kiely, 1997).

Parameter	Primary sludge	Anaerobocally digested sludge	Aerobically digested sludge
pH	5-8	6.5-7.5	
Alkalinity (mg/L as $CaCO_3$)	500-1500	2500-3500	
Nitrogen (N% of TS)	1.5-4	1.6-6	0.5-7.6
Phosphorus (P_2O_3% of TS)	0.8-2.8	1.5-4	1.1-5.5
Fats, grease (% of TS)	6-30	5-20	
Protein (% of TS)	20-30	15-20	
Organic acids (mg/L as HAc)	6800-10 000	2700-6800	

2.6 MICROBIOLOGICAL CHARACTERISTICS OF SEWAGE SLUDGE

Like raw wastewater, sludge may contain bacteria, viruses, protozoa, parasites and other microorganisms, some beneficial but some perhaps pathogenic. When wastewater is "purified" (via the primary settling, activated sludge basin, secondary settling, etc)., the pathogens become concentrated in the sludge. Therefore raw sludge contains the same infectious agents as raw sewage, but in significantly higher concentrations (table 8). Further treatment of sludge (conditioning, thickening, dewatering, etc.) is made to reduce the water content and concentrate the solids will also concentrate any pathogens present. The process of "sludge stabilization" is therefore required to reduce pathogens and simultaneously eliminate odors. Thus sludge applied to land or water or going into aerosol form may have the potential to impact negatively on human and biotic health. Microorganism species and density of sludge is related to the community from which it was derived, and particularly its pathogenic content. An important distinction of bacteria and viruses in sludge is that bacteria can increase in number in sludge while viruses cannot (the latter require mammalian host cells for replication) (Kiely, 1997).

Table 8. Levels of indicator and pathogenic organisms in sludge bacteria and viruses[1] (Kiely, 1997).

Sludge (untreated[2])	Total coliforms	Faecal coliforms	Faecal *Streptococci*	*Salmonella* species	*Pseudomonas aeruginosa*	Enteric viruses
Primary	10^6-10^8	10^6-10^7	≈ 10^6	$4 * 10^2$	$3 * 10^3$	0.002-0.004 MPN
Secondary	10^7-10^8	10^7-10^9	≈ 10^6	$9 * 10^4$	$1 * 10^4$	0.0015-0.026 MPN
Mixed	10^7-10^9	10^5-10^6	≈ 10^6	≈ $5 * 10^2$	≈ 10^3-10^5	

[1] The units are the number of organisms per gram of dry weight (GDW)

[2] Untreated means not yet stabilized, dewatered, anaerobically digested or composed etc.

The process of aerobic and anaerobic digestion, composting, heat treatment, lagooning, etc., all effectively reduces pathogens in sludge. Incineration and liming will totally eliminate pathogens. Disposal of sludge without the above treatment may include health (Kiely, 1997).

3. PRELIMINARY OPERATIONS

Sludge grinding, degritting, blending and storage are necessary to provide a relatively constant, homogeneous feed to sludge-processing facilities. Sludge grinding is a process in which large and stringy material contained in sludge is cut or sheared into small particles to prevent the clogging of or wrapping around rotating equipment (Tchobanoglous and Burton, 1991).

In some plants where separate grit removal facilities are not adequate to handle peak flows and peak grit loads, it may be necessary to remove the grit before further processing of the sludge. Where further thickening of the primary sludge is desired, a practical consideration is sludge degritting. The most effective method of degritting sludge is through the application of centrifugal forces in a flowing system to achieve separation of the grit particles from the organic sludge (Tchobanoglous and Burton, 1991).

Sludge is generated in primary, secondary and advanced wastewater treatment processes. Primary sludge consists of settleable solids carried in the raw wastewater. Secondary sludge consists of biological solids as well as settleable solids. Sludge produced in the advanced wastewater may consist of biological and chemical solids. Sludge is blended to produce a uniform mixture to downstream operations and processes. Uniform mixtures are most important in short detention time systems, such as sludge dewatering, heat treatment, and incineration. Provision of a well-blended sludge with consistent characteristics to these treatment units will greatly enhance plant operability and performance. Sludge from primary, secondary, and advanced processes can be blended in several ways including (Tchobanoglous and Burton, 1991):

- *In primary settling tanks*, where secondary or advanced wastewater treatment sludge can be returned to the primary settling tank to settle and mix with primary sludge
- *In pipes*, within the server network
- *In sludge processing facilities with long detention times*, such as in aerobic and anaerobic digesters blending the feed sludge uniformly
- *In a separate blending tank*, which provide the best opportunity to control the quality of the blended sludge.

Sludge storage must be provided to smooth out fluctuations in the rate of sludge production and to allow sludge to accumulate during periods when subsequent sludge processing facilities are not operating. Sludge storage is particularly important in providing a uniform feed rate ahead of the following processes: lime stabilization, heat treatment, mechanical dewatering, drying, and thermal reduction (see following sections in this chapter). Short-term sludge storage may be accomplished in wastewater settling tanks or in sludge thickening tanks. Long-term sludge storage may be accomplished in sludge stabilization processes with long detention times (*e.g.* aerobic and anaerobic digestion) or in specially designed separate tanks. If sludge is stored longer than two or three days, it will deteriorate and will be more difficult to dewater. Sludge is often aerated to prevent septicity and to promote mixing (Tchobanoglous and Burton, 1991).

4. THICKENING

Thickening is a procedure used to increase the solids content of thin sludge (0.2 to 5 percent) by removing a portion of the liquid fraction, typically about twice the dry solids content (Kiely, 1997). The volume reduction obtained by sludge concentration is beneficial to subsequent treatment processes, such as digestion, dewatering, drying, and combustion.

Within the concentration range of wastewater sludge, increasing the solids content by only a minimum percentage results in drastic reduction in the sludge volume (Donald *et al*, 1995). Because the size, and therefore cost, of sludge disposal facilities is a function of the volume of sludge to be handled, considerable savings can be attained by volume reduction (Donald *et al*, 1995). On large projects where sludge must be transported a significant distance, such as to a separate plant for processing, a reduction in sludge volume may result in a reduction of pipe size and pumping costs. Further, volume reduction is very desirable when liquid sludge is transported by tank trucks for direct application to land as a soil conditioner (Tchobanoglous and Burton, 1991).

Sludge thickening is achieved at all wastewater treatment plants in some manner – in the primary settlers, in sludge digestion facilities, or in specially designed separate units. In treatment plants with less than $0.044\text{m}^3/\text{s}$ (1Mgal/d) capacity, separate sludge thickening is seldom practiced. In small plants, gravity thickening is accomplished in the primary settling tank or in the sludge digestion units, or both. In larger treatment facilities, the additional cost of separate sludge thickening is often justified by the improved control over the thickening process and the higher concentrations attainable (Tchobanoglous and Burton, 1991).

Thickening is generally accomplished by physical means including gravity settling, flotation, centrifugation, and gravity belts (Hammer and Hammer, 1986). Mechanical methods such as vacuum filtration and centrifugation may be used where the sludge is subsequently to be handled in semisolid state (see chapter 7). These methods are commonly used preceding sludge incineration. Where further biological treatment is intended, volume reduction by gravity thickening and/or flotation is common practice. In both cases, the sludge remains in a liquid state (Donald *et al*, 1995).

4.1 GRAVITY THICKENING

Gravity thickening is accomplished in a tank similar in design to a conventional sedimentation tank. The thickening function is the major design parameter, and tanks are generally deeper than secondary settlers to provide greater thickening capacity (Donald *et al*, 1995).

Dilute sludge is fed to a center-feed well. The feed sludge is allowed to settle and compact, and the thickened sludge is withdrawn from the bottom of the tank. Conventional sludge collecting mechanisms with deep trusses or vertical pickets are used to stir the sludge gently, thereby opening up channels for water to escape and promoting densification (Kiely, 1997). The supernatant flow that results is returned to the primary settling tank or to the headwork of the treatment plant. The thickened sludge that collects on the bottom of the tank is pumped to the digesters or dewatering equipment as required; thus, storage space must be provided for the sludge. Gravity thickening is most effective on primary sludge (Hammer and Hammer, 1986). Retention times in gravity thickeners are typically (Kiely, 1997):

- 1 day for primary sludge
- 2 days for secondary sludge
- 7 days for digested sludge

A well-designed, well-operated gravity thickener should be able to, at least, double the solids content of the sludge, thereby eliminating half volume. It should be noted that the design of gravity thickeners should be based on the result of pilot-plant analysis wherever possible, since successful loading rates are highly dependent on the nature of the sludge (Donald *et al*, 1995).

4.2 FLOTATION THICKENING

Waste activated sludge does not thicken well in gravity thickeners and loading rates are significantly lower than for other sludge. Also, the effectiveness of gravity thickeners for primary sludge is diminished considerably by mixing with activated sludge. The light, flocculent nature of activated sludge lends itself quite well to flotation thickening, however, and the use of the process has been increasing in resent years (Donald *et al*, 1995).

The most commonly used flotation thickening operation is dissolved-air flotation (figure 5) where a small quantity of water, usually secondary effluent, is subjected to aeration under a pressure of about 400 kPa. This supersaturated liquid is then released near the bottom of the tank through which the sludge is passed at atmospheric pressure (Donald *et al*, 1995). The dissolved air is released as finely divided bubbles carrying the sludge to the top from where it is removed (Hammer and Hammer, 1986), while liquid is removed near the bottom and is returned to the aerator (Donald *et al*, 1995).

Flotation thickening is used most efficiently for waste sludge from suspended growth biological treatment processes, such as the activated sludge process or the suspended-growth nitrification process (Tchobanoglous and Burton, 1991).

Figure 2. Dissolved-air flotation unit used for thickening waste activated sludge (web ref 1).

4.3 CENTRIFUGAL THICKENING

Thickening by centrifugation involves the settling of sludge particles under the influence of centrifugal forces. Different types of centrifugal thickeners are explained in detail in chapter 7. The application in thickening is limited normally to waste activated sludge. Maintenance and power costs for the centrifugal thickening process, however, can be substantial. Therefore, the process is usually attractive only at facilities larger than 0.2 m^3/s (5 Mgal/d), where space is limited and skilled operators available, or for sludge that are difficult to thicken by more conventional means (Tchobanoglous and Burton, 1991).

4.4 GRAVITY BELT THICKENING

Gravity belt thickeners stem from the application of belt presses for sludge dewatering (see chapter 7). In belt-press dewatering, particularly for sludge with solids concentration of less than 2 percent, effective thickening occurs in the gravity drainage section of the press

(Hammer and Hammer, 1986). The equipment developed for the thickening consists of a gravity belt that moves over rollers driven by a variable-speed drive unit. The sludge is conditioned with polymer and fed into a feed/distribution bow at one end. The box is used to distribute the sludge evenly across the width of the moving belt as the water drains through and the sludge is carried toward the discharge end of the thickener. The sludge is ridged and furrowed by a series of plow blades placed along the travel of the belt, allowing the water released from the sludge to pass through the belt. Belt speed can be varied to attain the desired percentage of dry solids. After thickened sludge is removed, the belt travels through a wash cycle (Tchobanoglous and Burton, 1991).

The gravity belt thickener has been used for thickening raw and digested sludge. Thin sludge (0.2 to 2 percent) can be thickened more readily by the addition of polyelectrolytes (Kiely, 1997).

4.5 ROTARY DRUM THICKENING

Rotary media-covered drums are also used to thicken sludge. A rotary drum thickening system consists of a waste activated sludge conditioning system (including a polymer feed system) and rotating cylindrical screens. Polymer is mixed with thin sludge in the mixing and conditioning drum. The conditioned sludge is then passed to rotating screen drums, which separate the flocculated solids from water. Thickened sludge rolls out the end of the drums, while separated water decants through the screens (Kiely, 1997).

Advantages of rotary drum thickeners are low maintenance, low energy use, and small space requirements. Designs also allow coupling of the rotary drum unit with a belt filter press for combination of thickening and dewatering (Tchobanoglous and Burton, 1991).

5. STABILISATION

Stabilization of sludge is a process that renders the sludge or sludge end products nearly pathogen free. Much recent legislative emphasizes successfully stabilizing sludge or compost products. In addition to pathogen reduction, odor reduction and elimination of putrefaction are also achievable by stabilization (Kiely, 1997).

The success in achieving these objectives is related to the effects of the stabilization operation or process on the volatile organic fraction of the sludge. Survival of pathogens, release of odors, and putrefaction occur when micro-organisms are allowed to flourish in the organic fraction of the sludge, the means to eliminate these nuisance condition through stabilization are (Tchobanoglous and Burton, 1991):

- the biological reduction of volatile content,
- the chemical oxidation of volatile matter,
- the addition of chemicals to the sludge to render it unsuitable for the survival of micro-organisms and,
- the application of heat to disinfect or sterilize the sludge.

The technologies for sludge stabilization discussed in this text include lime stabilization, anaerobic digestion and aerobic digestion. Composting and heat treatment is also technologies used for stabilization and is further discussed in section 8.3 and section 6.2 respectively.

5.1 LIME STABILISATION

In the lime stabilization process, lime is added to untreated sludge in sufficient quantity to raise the pH to 12 or higher. The high pH creates an environment that is not conductive to the survival of micro-organisms. Consequently, the sludge will not putrefy, creates odors, or pose a health hazard, so long as the pH is maintained at this level (Tchobanoglous and Burton, 1991). However, recent research has indicated that micro-organisms regrowth may occur if the pH level is lowered (Kiely, 1997).

Either hydrated lime, $Ca(OH)_2$, or quicklime CaO, may be used for lime stabilization. Fly ash, cement kiln dust, and carbide lime have also been used as a substitute for lime in some cases (Tchobanoglous and Burton, 1991). The lime may be added before or after dewatering (Kiely, 1997).

The use of lime is a low capital cost operation but may be high in operation cost unless the purchase of the lime, i.e. as cement kiln dust, is cheap. Lime stabilization is becoming an outdated technique as the weight of the post-limed sludge has increased by 20 to 40 percent of its initial weight. This is so because the amount of lime added ranges from 100 to 200 kg/tone of DS (Kiely, 1997).

5.2 ANAEROBIC DIGESTION

Anaerobic digestion is among the oldest forms of biological wastewater treatment, and its history can be traced back to the 1850s with the development of the first tank designed to separate and retain solids. Because of the emphasis on energy conservation and recovery and the desirability of obtaining beneficial use of wastewater sludge, anaerobic digestion continues to be the dominant sludge stabilization process (Tchobanoglous and Burton, 1991).

Sludge digestion serves both to reduce the volume of the thickened sludge still further and to render the remaining solids inert and relatively pathogen-free (Donald *et al*, 1995).

By definition, anaerobic digestion is “the use of microbial organisms, in the absence of oxygen, for stabilization of organic materials by conversion to methane and inorganic products including carbon dioxide” (Kiely, 1997). In other words this can be described as:

$$\text{Organic matter} + H_2O - \text{anaerobes} \circledR$$
$$CH_4 + CO_2 + \text{new biomass} + NH_3 + H_2S + \text{heat}$$

Anaerobic digestion is by far the most common process for dealing with wastewater sludge containing primary sludge as it contains a high amount of organic matter (Donald *et al*, 1995). However, waste activated sludge can also be digested on its own but is often mixed with primary sewage sludge (Kiely, 1997). Sludge containing large amounts of readily available organic matter would induce a rapid growth of biomass if treated aerobically. Anaerobic decomposition produces considerably less biomass than aerobic processes. The principal function of anaerobic digestion, therefore, is to convert as much of the sludge as possible to end products such as liquids and gases while producing as little residual biomass as possible (Hammer, 1986).

The anaerobic digestion of sewage sludge is commonplace where the gas is optimized and used as part of the waste treatment plant energy budget. Typically, about 50 to 60 percent of the organics are metabolized, with less than 10 percent being converted to biomass (Donald *et al*, 1995). The chemical oxygen demand (COD) reduction ranges from 75 to 90 percent. It therefore needs further treatment, usually aerobically. The benefits using anaerobic digestion of sludge include (Kiely, 1997):

- Methane production
- 30 to 50 percent reduction in sludge volume
- Odor-free sludge end-product
- Elimination of pathogens and weed seeds (if mesophillic or thermophillic)
- Reduction of pollution potential waste
- Improvement in fertilizer/fuel value of waste product

5.2.1 Microbiology of anaerobic digestion

Wastewater sludge contains a wide variety of organisms, and thus requires a wide variety of organisms for its decomposition. The literature relating to anaerobic sludge digestion often divides the organisms into broad groups, the acid formers and the methane formers. The acid formers consists of faculative and anaerobic bacteria and include organisms that solubilize the organic solids. The methane formers convert molecules into methane (Donald *et al*, 1995). It is the cumulative effect of all these groups that ensures process continuity and stability (Kiely, 1997).

Initially, the complex polymeric materials such as proteins, carbonhydrates, lipids, fats and grease are hydrolysed by extracelluar enzymes to simpler soluble products of a size small enough to allow their passage across the cell membrane of the microorganisms. These simple compounds of amino acids, sugar, fatty acids and alcohols are fermented to short-chain fatty acids, alcohols, ammonia, hydrogen and carbon dioxide. These short-chain fatty are converted to acetate, hydrogen and carbon dioxide. The final stage is methane production from hydrogen. The anaerobic process can thus be organized into seven subprocesses as follows (Kiely, 1997):

- Hydrolyses of complex particulate organic matter
- Fermentation of amino acids and sugar
- Anaerobic oxidation of long-chain fatty acids and alcohols
- Anaerobic oxidation of intermediary products
- Acetate production from CO_2 and H_2
- Conversion of acetate to methane by aceticlastic methanogens
- Methane production by hydrogenophilic methanogens using CO_2 and H_2O.

The biological agents of anaerobic digestion are bacteria but fermentative ciliate and flagellate protozoa and some anaerobic fungi may play minor roles in some systems. The huge range of genera and species indicates the complex nature of microbal population and in each of the stages the population densities in sewage sludge range from 10^5 to 10^9 per mL (table 9) (Kiely, 1997).

Table 9. Some bacterial species in anaerobic digestion (Adapted from Kiely, 1997, and others).

Stage	Genera/species	Population in mesophillic sewage sludge
Hydrolytic acidogenic	*Butyrivibrio, Clostridium, Ruminococcus, Acetividrio, Eubacterium, Peptococcus, Lactabacillius, Streptococcus,* etc.	$10^8 – 10^9$ per ml
Acetogenic		
Homoacentogenic	*Acetobacterium, Acetogenium, Eubacterium, Pelobacter, Clostridium,* ect.	≈ 10^5 per ml
Obligate proton reducing acetogens	*Methanobacillus omelionskii, Syntrophobacter wolinii, Syntrophomonas wolfei, Syntrophus buswelli,* etc.	
Methanogenic[1]	*Methanobecterium, Methanobrevibacter, Methanococcus, Methanomicrobium, Methanogenium, Methanospirillium hungatei,* etc.	≈10^8 per ml

[1] The methanogenic bacteria are usually the limiting population.

Operation of anaerobic digesters is complicated by the delicate nature of the methane formers. These organisms are strict anaerobes and function within a narrow pH range of from 6.5 to 7.5 units. These organisms are also sensitive to sudden changes in other environmental factors such as temperature, food supply, etc. Shock loading (addition of large amounts of raw sludge within a short period) can be disastrous to anaerobic digesters. The acid formers respond quickly to the increased food supply and produce increased amounts of acids. The methane formers cannot respond as quickly and the acid accumulates, lowering the pH of the digester. Once the pH-tolerable level of the methane formers is reached, methane production ceases and the pH can be lowered to the toxic level of acid formers unless the situation is rectified quickly. The buffering capacity of the digester is therefore very important. Fortunately, the alkalinity of the digesting sludge in naturally high because of the solubilization of carbon dioxide (CO_2) produced by biological processes, and its subsequent conversion to nitric acid (HCO_3). A sudden reduction in alkalinity heralds a pH drop, and more alkalinity, usually in the form of lime, must be added to maintain the buffering capacity (Donald *et al*, 1995).

5.2.2 Gas production

Product gases from anaerobic digestion typically contain 65 to 70 percent methane, 25 to 30 percent CO_2, and the trace amounts of other gases, such as nitrogen (N_2), hydrogen (H_2) and hydrogen sulphide (H_2S), and water vapor (Donald *et al*, 1995). Digester gas production is one of the best measures of the progress of digestion. Total gas production is estimated usually from the percentage of volatile solids reduction. Typical values vary from 0.75 to 1.12 m^3/kg of volatile solids destroyed. Gas production can fluctuate over a wide range, depending on the volatile solids content of the sludge feed and the biological activity in the digester. Gas production can also be crudely estimated on a per capita basis. The normal yield is 15 to 22 $m^3/10^3$ persons ×d in primary plants treating normal domestic water. In secondary treatment plants, the gas production is increased to about 28$m^3/10^3$ person ×day (Tchobanoglous and Burton, 1991).

Digester gas is collected under the cover of the digester and must not be allowed to mix with air, or an explosive mixture may result. Gas can be stored either at low pressure in external gasholders that use floating covers or at high pressure in pressure vessels if gas compressors are used (Tchobanoglous and Burton, 1991).

Methane gas at standard temperature and pressure has a net heating value of 35,800 kJ/ m^3. Because digester gas is typically about 65 percent methane, the low heating value of digester gas is approximately 37,300 kJ/ m^3. By comparison, natural gas, which is a mixture of methane, propane, and butane, has a low heating value of approximately 22,400 kJ/ m^3. In large plants, digester gas may be used as fuel for boiler and internal combustion engines, which are in turn used for pumping wastewater, operating blowers, and generating electricity. Hot water from heating boilers or from engine jackets and exhaust heat boilers may be used for sludge heating and for building heating, or gasfired sludge heating boilers may be used (Hammer, 1986).

5.2.3 Reactor configuration

The basic (complete mix – no media) reactor process is shown in figure 6 (see page 566, Basic anaerobic digestion process). The low-rate conventional system shown is made up of several layers. The influent sludge enters the tank close to the top at the location of the supernatant layer (a partially purified liquid layer). Below this is a layer of actively digesting sludge and at the bottom of the tank sits the stabilized sludge, ready for abstraction (withdrawal) (Kiely, 1997).

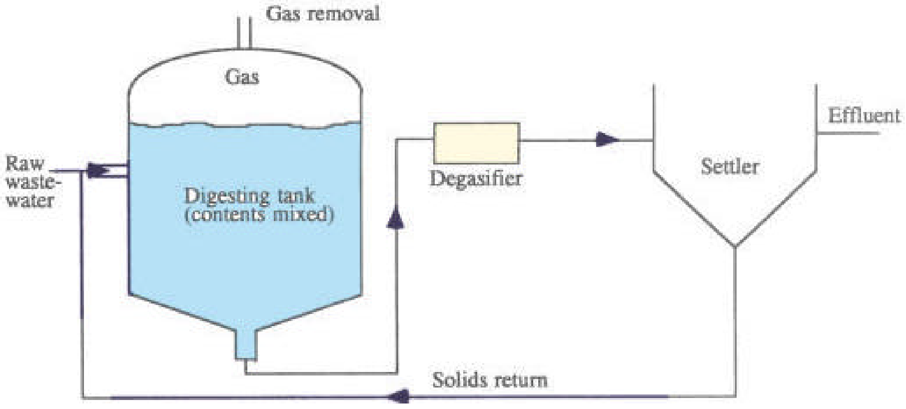

Figure 6. Basic anaerobic digestion process (Kiely, 1997) (web ref 2).

Proper digester mixing is one of the most important considerations in achieving optimum process performance. The most common types involve the use of gas injection, mechanical stirring, and mechanical pumping (Tchobanoglous and Burton, 1991).

The supernatant withdraw from the digester contains large amounts of solubilized organics and solids. This material must be circulated back through the plant for further treatment. Solids withdrawn from the bottom of the digester should be relatively inert (Donald *et al*, 1995).

5.3 ANEROBIC DIGESTION

Sludge can also be stabilized by aerobic digestion. Generally restricted to activated sludge in the absence of primary sludge, this process is essentially a continuation of the aeration process, with the volume being reduced by thickening in the secondary settling tank and sludge thickener (Donald *et al*, 1995). A mixture of waste activated sludge or trickling-filter sludge and primary sludge can also be aerobically digested (Tchobanoglous and Burton, 1991). The most common application of aerobic digestion involves stabilizing sludge waste from extended aeration systems (Donald *et al*, 1995).

Advantages claimed for aerobic digestion as compared to anaerobic digestion are as follows (Tchobanoglous and Burton, 1991 and Kiely, 1997):

- Production of an odorless, humus-like, biologically stable end product
- Low capital cost
- Easy operation
- Non-explosive gas (CO_2 and NH_3)
- More purified supernatant than in anaerobic digestion
- Volatile solids reduction is approximately equal to that obtained anaerobically
- Recovery of more of the basic fertilizer values in the sludge

The major disadvantages of the aerobic digestion process are that (Tchobanoglous and Burton, 1991and Kiely, 1997):

- High operation costs for power and oxygen
- A digested sludge is produced with poor mechanical dewatering characteristics
- The process is affected significantly by temperature, location, and type of tank material
- The useful by product of methane is not recovered

Aerobic digestion is somewhat similar to the activated sludge process. Sludge is fed to a tank where it is mixed aerobically. The main objective of the process is to reduce the solids content for ultimate disposal. The volatile solids are reduced as in anaerobic digestion and thus stabilized highly fertilizable humus is produced (Kiely, 1997). As the supply of available substrate (food) is depleted, the microorganisms begin to consume their own protoplasm to obtain energy for cell maintenance reactions (Donald *et al*, 1995). When this occurs, the microorganisms are said to be in the endogenous phase. Cell tissue is oxidized aerobically to carbon dioxide, water, and ammonia. In reality, only about 75 to 80 percent of the cell tissue can be oxidized; the remaining 20 to 25 percent is composed of inert components and organic compounds that are not biodegradable. The ammonia from this oxidation is subsequently oxidized to nitrate as digestion proceeds. The resulting overall reaction is given by the following equation (Tchobanoglous and Burton, 1991):

$$\text{Eq. I} \quad C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + NO_3^- + 3H_20 + H^+$$

As shown in equation I, a pH drop can occur when ammonia is oxidized to nitrate if the alkalinity of the wastewater is insufficient to buffer the solution. Where activated trickling filter sludge is mixed with primary sludge and the combination is to be digested aerobically, there will be both direct oxidation of the organic matter in the primary sludge and endogenous oxidation of the cell tissue (Tchobanoglous and Burton, 1991).

Because the majority of aerobic digesters are open tanks, digester liquid temperatures are dependent on the weather conditions and can fluctuate extensively. As with all biological systems, lower temperatures retard the process, whereas higher temperatures accelerate it (Kiely, 1997). Heat losses are minimized by using concrete instead of steel tanks, placing the tanks below grade instead of above grade or providing insulation for above-ground tanks, and using subsurface instead of surface aeration (Hammer, 1986).

6. CONDITIONING

Sludge conditioning is chemical or thermal treatment of sludge to improve the efficiency of thickening and dewatering (Kiely, 1997). The two methods most commonly used involve the addition of chemicals and heat treatment (Tchobanoglous and Burton, 1991).

6.1 CHEMCAL CONDITIONING

The use of chemicals to condition sludge is economical because of the increased yields and greater flexibility obtained. Chemical conditioning can reduce the 90 to 99 percent incoming sludge moisture content to 65 to 85 percent, depending on the nature of the solids to be treated. Chemical conditioning results in the coagulation of the solids and release of the absorbed water. Intimate admixing of sludge and coagulant is essential for proper conditioning. The mixing must not break the floc after it has formed, and the detention should be kept to a minimum so that sludge reaches the dewatering unit as soon after conditioning as possible (Tchobanoglous and Burton, 1991).

Factors that affect the selection and dosage of sludge conditioning agents include the sludge properties and the type of mixing, dewatering and thickening devices to be used. Important sludge properties are sludge source (table 1), solids concentration, age, pH, and alkalinity. Sludge sources such as primary sludge, waste activated sludge, and digested sludge is good indicators on the range of probable conditioner doses required. Solids concentrations will affect the dosage and the dispersal of the conditioning agents, in particular the inorganic conditioners. In general it has been observed that the type of sludge has the grates impact on the quantity of chemical required. (Tchobanoglous and Burton, 1991).

Most common chemical used are either inorganic chemicals or organic polyelectrolytes. The inorganic chemicals used include (Tchobanoglous and Burton, 1991 and Kiely, 1997):

- Ferric chloride
- Lime
- Ferrous sulphate + lime
- Alum

These are usable principally for conditioning secondary sludge or combined secondary and primary sludge. Their disadvantage is that for each kilogram of inorganic chemicals added, an extra kilogram of sludge is produced. The dose range of inorganic chemicals is 100 to 200 kg/ton of DS (Kiely, 1997). Lime can increase the solids by 20 to 30 percent. When lime is used strong ammonia odor and lime scaling problems may also occur. Factors that affect the dosages of ferric chloride and lime include the type of sludge (primary, secondary, or a mixture) and the type of stabilization process, if any, used prior to dewatering (Tchobanoglous and Burton, 1991).

Organic polyelectrolytes or polymers are used in all sludge types and have the advantage of producing less significant increase in sludge volume. The amount of polymer added is in the range of 2 to 100 kg/ton of DS, but is most typically about 6 kg/ton DS (Kiely, 1997). The required dose of polyelectrolytes is critical to the performance of the dewatering equipment and to the cost of the operation. The dose is determined by pilot plant test or bench tests and may be required to change from time to time as the sludge quality changes (Kiely, 1997).

Polymer dosage will vary greatly depending on the molecular weight, ionic strength, and activity level of the polymers used (Tchobanoglous and Burton, 1991).

The choice of polyelectrolytes depends on the dewatering technology, filter presses, filter belts, centrifuges, etc. Organic polymers are typically long-chain, water-soluble synthetic organic chemicals and commonly cationic polyacrylamides to destabilize the ionic charge of sludge solids. They are usually supplied in liquid dispersion and are categorized by (Kiely, 1997):

- Molecular weight (0.5 to $18*10^6$)
- Charge density (10 to 100 percent)
- Active solid level (2 to 95 percent)

Many polyselectrolytes are high of molecular weight (about 106) and of high charge density. The latter can neutralise the very fine solids in biomass. The high molecular weight provides the floc strength to withstand the shear forces produced by the dewatering equipment, e.g. belt presses and centrifuges (see chapter 7) (Kiely, 1997).

6.2 HEAT TREATMENT

Heating the sludge under pressure is a technique receiving much attention (Kiely, 1997). Heat treatment is a continuous process in which sludge is heated in a pressure vessel to temperatures up to 260°C (500°F) at pressures up to 2760 kN/m^2 for short periods of time (approximately 30min) (Tchobanoglous and Burton, 1991).

Heat treatment serves essentially as both a stabilization process (see chapter 5) and a conditioning process (see chapter 6); in most cases, it is classified as a conditioning process. Heat treatment conditions the sludge by rendering the solids capable of being dewatered without the use of chemicals. Heat treatment is used to coagulate solids, to break down the gel structure, and to reduce the water affinity of sludge solids. When the sludge is subjected to the high temperatures and pressures, the thermal activity releases bound water and result in the coagulation of solids. In addition, hydrolysis of proteinaceous materials occurs, resulting in cell destruction and release of soluble organic compounds and ammonia nitrogen. As a result, the sludge is sterilized and dewatered readily. The heat treatment process is most applicable to biological sledges that may be difficult to stabilize or condition by other means. Advantages cited for heat treatment are that (Tchobanoglous and Burton, 1991):

- the solids content of dewatered sludge can range from 30 to 50 percent, depending on the degree of oxidation achieved,
- the processed sludge does not normally require chemical conditioning,
- the process stabilizes sludge and will destroy most pathogenic organisms,
- the processed sludge will have a heating volume of 28 to 30 kJ/g of volatile solids and,
- the process is relatively insensitive to changes in sludge composition.

The major disadvantages associated heat treatment can be attributed to (Tchobanoglous and Burton, 1991):

- high capital costs due to its mechanical complexity and the use of corrosion resistant materials,
- close supervision, skilled operators, and strong preventive maintenance program are required,
- the process producers side streams with high concentration of organics, ammonia nitrogen, and color,
- significant odorous gases are produced that require extensive containment, treatment and/or destruction, and
- seale formation in the heat exchangers, pipes, and reactor requires acid washing or high pressure water jets.

7. DEWATERING

As explained in chapter 4 thickening increases sludge concentration to about twice the dry solids content. Dewatering is a similar process but has the objective of taking as much water as possible from the sludge (Kiely, 1997). It is a physical (mechanical) unit operation used for one or more of the following reasons (Tchobanoglous and Burton, 1991):

- The costs for trucking sludge to the ultimate disposal site become substantially lower when sludge volume is reduced by dewatering.
- Dewatered sludge is generally easier to handle than thickened or liquid sludge.
- Dewatering is required normally prior to the incineration of the sludge to increase the energy content by removal of excess moisture.
- Dewatering is required before composting to reduce the requirements for supplemental bulking agents or amendments.
- In some cases, removal of the excess moisture may be required to render the sludge odorless and nonputrescible.
- Sludge dewatering is required prior to landfilling in monofills to reduce leachate production at the landfill site.

A number of techniques are used in dewatering devices for removing moisture. Some rely on natural evaporation and percolation to dewater the solids. In mechanical dewatering devices, mechanically assist physical means are used to dewater the sludge more quickly. The physical means include filtration, squeezing, capillary action, vacuum withdrawal, and centrifugal separation and compaction (Hammer and Hammer, 1986).

The selection of dewatering device is determined by the type of sludge to be dewatered, characteristics of the dewatered product, and the space available. For smaller plants where land availability is not a problem, drying beds or lagoons are generally used. Conversely, for facilities situated on constricted sites, mechanic dewatering devices are often chosen. Some sludge, particularly aerobically digested sludge, are not amenable mechanical dewatering. This sludge can be dewatered on sand beds with good results (Kiely, 1997). This chapter discusses the most common methods for dewatering, namely:

- Vacuum filters
- Centrifuges
- Belt filter press
- Recessed plate filter presses
- Sludge drying beds
- Sludge lagoons
- Sludge ponds
- Sludge freezing beds

Table 10 shows the approximate solid content of dewatered sludge depending on the dewatering method that has been used.

Table 10. Solids content of dewatered sludge (Donald *et al*, 1995).

Method	Approximate solids content, %
Vacuum filtration	20-30
Centrifuge	20-25
Filter press	30-45
Drying beds	40
Ponds	30

7.1 VACCUM FILTRATION

In vacuum filtration, atmospheric pressure, due to vacuum applied downstream of the filter media, is the driving force on the liquid phase that causes it to move through the porous media. The vacuum filter consists of a horizontal cylindrical drum that rotates partially submerged in a vat of conditioned sludge. The surface of the drum is covered with a porous medium, the selection of which is based on the sludge dewatering characteristics. Types of filter medium commonly used are cloth belts or coiled springs. The drum surface is divided into sections around its circumference. Each section is sealed from its adjacent sections and the ends of the drum. A separate vacuum/drain line connects each section to a rotary valve at the axis of the drum. The rotary valve controls the various phases of the filtering cycle and channels filtrate away from the drum. As the drum rotates the valve allows each segment to function in sequence as one of three distinct zones; cake formation, cake dewatering, and cake discharge. Chemical conditioning of the sludge prior to filtration is practiced to increase the solids content, to reduce filtrate solids, and to improve the dewatering characteristics (Tchobanoglous and Burton, 1991).

7.2 CENTIFUGATION

For separating liquids of different density, thickening slurries, or removing solids, the centrifugation process is widely used in the industry. The process is applicable to the dewatering of wastewater sludge and has been used with varying degrees of success. The centrifugal devices used for thickening sludge are solid bowl and imperforate basket centrifuges (see chapter 4). These may also be used for sludge dewatering (Tchobanoglous and Burton, 1991). The principal differences between thickening and dewatering centrifuges are the configureation of conveyor or scroll towards the liquids discharge and the location and configureation of the solids discharge ports (Kiely, 1997).

7.2.1 Solid Bowl Centrifuge

In the solid bowl machine (figure 7), sludge is fed at a constant flow rate into the rotating bowl, where it separates into a dense cake containing the solids, and a dilute stream called "centrate". The centrate contains of fine low-density solids and is returned to the wastewater treatment system. The sludge cake, which contains approximately 70 to 80 percent moisture, is discharged from the bowl by a screw feeder into a hopper or onto a conveyor belt (Kiely, 1997).

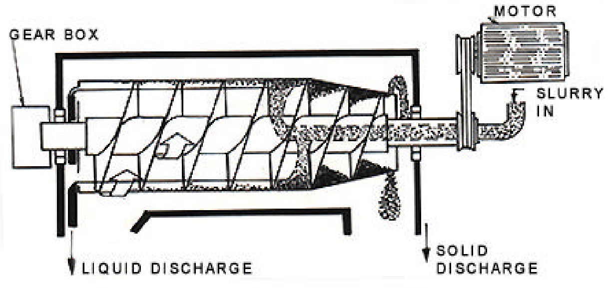

Figure 7. Solid bowl centrifuge (web ref 3).

Solid bowl centrifuges are suitable generally for a variety of sludge dewatering applications. The units can be used to dewater sludge with no prior chemical conditioning, but the solids capture and centrate quality are improved considerably when solids are conditioned with polymers (Tchobanoglous and Burton, 1991).

7.2.2 Imperforate basket centrifuge

Imperforate basket centrifuges (figure 8) are particularly suitable for small plants. For these applications, basket centrifuges can be used to concentrate and dewater waste activated sludge, with no chemical conditioning, at solids capture rates up to 90 percent (Tchobanoglous and Burton, 1991).

The imperforate basket centrifuge operates on a batch basis. The liquid sludge is introduced into a vertically mounted spinning bowl. The solids accumulate against the wall of the bowl and the centrate is decanted. When the solids-holding capacity of the machine has been achieved, the bowl decelerates and a scraper is positioned in the bowl to help remove the accumulated solids (Tchobanoglous and Burton, 1991).

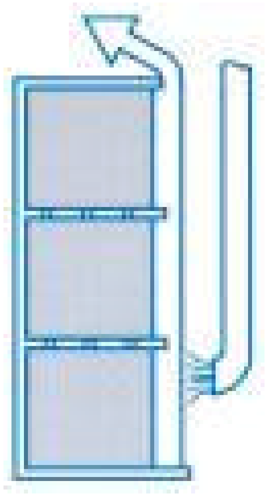

Figure 8. Imperforate basket centrifuge (web ref 4).

The imperforate basket centrifuge is particularly well suited for soft or fine solids that are difficult to filter or where the nature of the solids varies widely. The major difficulty encountered in the operation of centrifuges has been the disposal of the centrate, which is relatively high in suspended, non-settling solids. The return of these solids to the influent of the wastewater treatment plant has resulted in the passage of these fine solids through the treatment system, thereby reducing the effluent quality. Two methods can be used to control the fine solids discharge and to increase the capture; increased residence time or chemical conditioning (Tchobanoglous and Burton, 1991).

7.3 BELT FILTER PRESS

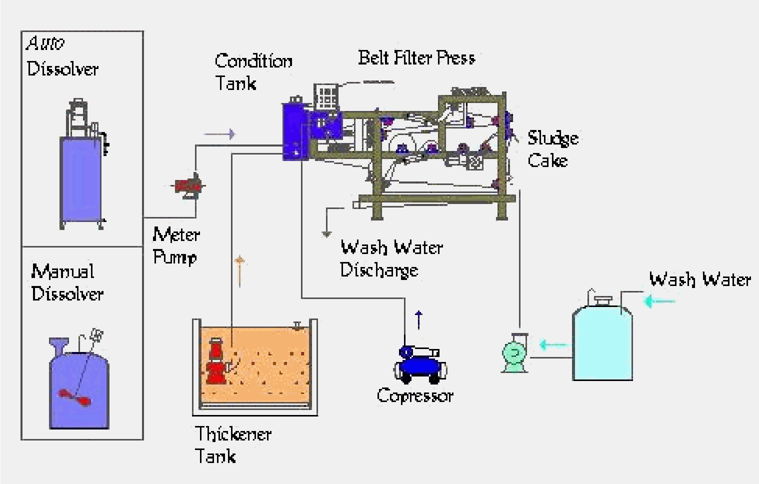

Figure 9. Three basic stages of belt press dewatering (web ref 5).

Belt filter presses are continuous-feed dewatering devices that involve the application of chemical conditioning, gravity drainage, and mechanically applied pressure to dewater sludge. The method is one of the predominant sludge-dewatering devices and proven to be effective for almost all types of municipal wastewater sludge (Tchobanoglous and Burton, 1991).

In most type of belt filter presses (figure 9), conditioned sludge is first introduced on a gravity drainage section where it is allowed to thicken. In this section, a majority of the free water is removed from the sludge by gravity. On some units, this section is provided with a vacuum assists, which enhances drainage and may help to reduce odors. Following gravity drainage, pressure is applied in a low-pressure section, where the sludge is squeezed between opposing porous cloth belts. On some units, the low-pressure section is followed by a high-pressure section, where the sludge is subjected to shearing forces as the belts pass through a series of rollers. The squeezing and shearing forces thus induce the release of additional quantities of water from the sludge. The final dewatered sludge cake is removed from the belts by scraper blades (Tchobanoglous and Burton, 1991).

7.4 FILTER PRESSES

While the belt press can be used for small municipalities, the filter press is more suitable for large population municipalities. In a filter press, dewatering is achieved by forcing the water from the sludge under high pressure. Advantages cited for the filter press includes high concentrations of cake solids, filtrate clarity, and high solids capture. Disadvantages include mechanical complexity, high chemical costs, high labor costs, and limitations on filter cloth life (Hammer and Hammer, 1986).

Various types of filter presses have been used to dewater sludge. The two types used most commonly are the fixed-volume and variable-volume recessed plate filter presses (Kiely, 1997).

7.4.1 Fixed-Volume, Recessed Plate Filter Presses

The fixed-volume, recessed plate filter press (figure 10) consists of a series of rectangular plates, recessed on both sides, that are supported face to face in a vertical position on a frame with a fixed and movable head. A filter cloth is hung or fitted over each plate. The plates are held together with sufficient force to seal them so as to withstand the pressure applied during the filtration process. Chemically conditioned sludge is pumped into the space between the plates and pressure of 690 to 1550 kN/m2 is applied and maintained for 1 to 3 hours, forcing the liquid through the filter cloth and plate outlet ports. The plates are then separated and the sludge is removed. The filtrate is normally returned to the headworks of the treatment plant (Tchobanoglous and Burton, 1991).

The sludge cake thickness varies from about 25 to 33 mm, and the moisture content varies from 48 to 70 percent. The filtration cycle time varies from 2 to 5 hours and includes the time required to fill the press, maintain the press under pressure, open the press, wash and discharge the cake, and close the press. Depending on the degree of automation incorporated into the machine, operator attention must be devoted to the filter press during feed, discharge, and wash intervals (Kiely, 1997).

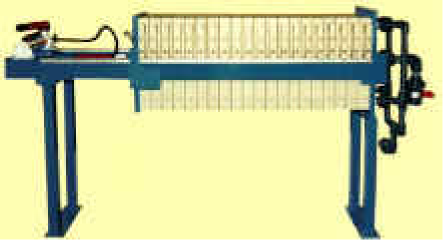

Figure 10 The fixed-volume, recessed plate filter press (web ref 6).

7.4.2 Variable-volume, Recessed plate filter presses

As mentioned, another type of filter press used for wastewater sludge dewatering is the variable-volume recessed plate filter press, commonly called the “diaphragm press”. This type of filter press is similar to the fixed-volume press except that a rubber diaphragm is placed behind the filter media. The rubber diaphragm expands to achieve the final squeeze pressure, thus reducing the cake volume during the compression step. Generally about 10 to 20 minutes are required to fill the press and 15 to 30 minutes of constant pressure are required to dewater the cake to the desired solids content. Variable-volume presses can handle a wide variety of sludge with good performance results, but require considerable maintenance (Tchobanoglous and Burton, 1991).

7.5 SLUDGE DRYING BEDS

Sludge drying beds are typically used to dewater digested sludge. After the air drying, the sludge is removed and either disposed in a landfill or used as a soil conditioner. The principal advantages of drying beds are low cost, infrequent attention required, and high solids content in the dried product (Tchobanoglous and Burton, 1991). Four types of drying beds are used; conventional sand, paved, artificial media, and vacuum-assisted.

7.5.1 Conventional sand drying beds

Conventional sand drying beds are generally used for small- and medium-sized communities. For cities with populations over 20,000, consideration should be given to alternative means of sludge dewatering. In large municipalities, the initial cost, the cost of removing the sludge and replacing sand, and the large area requirements generally preclude the use of sand drying beds (Kiely, 1997).

In a typical sand drying bed (figure 11), sludge is placed on the bed in a 200 to 300 mm layer and allowed to dry. Sludge dewaters by drainage through the sludge mass and supporting sand and by evaporation from the surface exposed to the air. Most of the water leaves the sludge by drainage, thus an adequate under-drainage system is essential. Drying beds are equipped with lateral drainage lines, sloped at a minimum of 1 percent and spaced 2.5 to 6 m apart. The drainage lines need to be adequately supported and covered with coarse gravel or crushed stone. The sand layer is from 230 to 300 mm deep with an allowance for some loss from cleaning operations. Deeper sand layers generally retard the draining process. The drying area is partitioned into individual beds approximately 6 m wide by 6 to 30 m long, or a convenient size so that one or two beds will be filled in a normal loading cycle. Sludge can finally be removed from the drying bed after it has drained and dried sufficiently to be spadable. Sludge removal is accomplished by manual shoveling into wheelbarrows or trucks or by a scraper or front-end loader. Dried sludge has coarse, cracked surface and is black or dark brown and its moisture content is approximately 60 percent after 10 to 15 days under favorable conditions (Tchobanoglous and Burton, 1991).

Figure 11. Typical sand drying beds (web ref 7).

Open beds are used where adequate area is available and is sufficiently isolated to avoid complaints caused by occasional odors. Covered beds with greenhouse types of enclosures are used where it is necessary to dewater sludge continuously throughout the year regardless of the weather and where sufficient isolation does not exist for the installation of open beds. With covered drying beds, more sludge can be applied per year because of the protection from rain and snow. In cold climates, the effects of freezing and thawing convert the jelly-like consistency of sludge to a granular-type material that drains readily (Tchobanoglous and Burton, 1991).

7.5.2 Paved drying beds

Two types of paved drying beds have been used as an alternative to sand drying beds; a drainage type and a decanting type. The drainage type function similarly to a conventional bed in that underdrainage is collected, but sludge removal is improved by using a front-end loader. The beds are normally rectangular in shape and are 6 to 15m wide by 21 to 46m long with vertical sidewalls. Concrete or bituminous concrete linings are used, overlaying a 200 to 300 mm sand or gravel base. For a given amount of sludge, this type of paved drying bed requires more area than conventional sand beds (Tchobanoglous and Burton, 1991).

The decanting type paved drying bed is advantageous for warm, arid and semi-arid climates. This type of drying bed uses low-cost impermeable paved beds that depend on the decanting of the supernatant and mixing of the drying sludge for enhanced evaporation. Decanting may remove about 20 to 30 percent of the water with a good settling sludge. Solids concentration may range from 40 to 50 percent for a 30 to 40 day drying time in an arid climate for a 300 mm sludge layer (Tchobanoglous and Burton, 1991).

7.5.3 Artificial media drying beds

Developments in drying bed design include using artificial media such as stainless steel wedge wire or high-density polyrethane formed into panels. In a wedge wire drying bed, liquid sludge is introduced onto a horizontal, relatively open drainage medium. The medium consists of small stainless steel wedge-shaped bars, with the flat part of the wedge on top. The slotted openings between the bars are 25mm wide and the wedge wire is formed into panels and installed in a false floor. An outlet valve is used to control the flow of drainage (Tchobanoglous and Burton, 1991).

7.5.4 Vacuum-assisted drying beds

A method used to accelerate dewatering and drying is the vacuum assisted sludge drying bed, where dewatering and drying is assisted by the application of a vacuum to the underside of porous filter plates. The principal advantages cited for this method are the reduced cycle time required for sludge dewatering, thereby reducing the effects of weather on sludge drying, and the smaller area required as compared to other types of drying beds (Tchobanoglous and Burton, 1991).

7.6 LAGOONS

Drying lagoons may be used as a substitute for drying beds for the dewatering of digested sludge and are more common for industrial plants or large municipalities with available land space (Kiely, 1997).

Unconditioned digested sludge is discharged to the lagoon in a manner suitable to accomplish an even distribution of sludge. Sludge depths usually range from 0.75 to 1.25 m. Evaporation is the prime mechanism for dewatering. Facilities for the decanting of supernatant are usually provided, and the liquid is recycled to the treatment facilities (Tchobanoglous and Burton, 1991). The cycle time for lagoons varies from several months to several years. Typically, sludge is pumped to the lagoon for 18 months, and then the lagoon is rested for 6 month (Kiely, 1997). Dewatering by subsurface drainage and percolation is limited by increasingly stringent environmental and groundwater regulations.

Lagoons are not suitable for dewatering untreated sludge, limed sludge, or sludge with a high strength supernatant because of their odor and nuisance potential. The performance of lagoons, like that of drying beds, is affected by climate; precipitation and low temperatures inhibit dewatering. Thus, lagoons are most applicable in areas with high evaporation rates (Tchobanoglous and Burton, 1991). The solid loading of lagoons is very low by comparison with mechanical dewatering systems (Kiely, 1997).

7.7 SLUDGE PONDS

Another popular form of dewatering of digested sludge is the sludge pond. The solids consolidate in the bottom while the supernatant is periodically removed from the top and recycled for re-treatment. When the solids have accumulated to a pre-selected depth, the pond is taken out of service and allowed to dry out. The dried sludge is then removed for final disposal (Donald *et al*, 1995).

7.8 SLUDGE FREEZING BEDS

Freezing beds is a system that is rarely used but in experimental facilities has been shown to be extremely successful though not necessarily economic. The freezing bed is known to be most effective for alum sludge and may be a consideration for cold climates (Kiely, 1997).

8. DISINFECTION

Sludge disinfection has become an important consideration as an add-on process because of stricter regulations for the use and application of sludge on land. When sludge is applied to the land, protection of public health requires that contact with pathogenic organisms be controlled. There are many ways to destroy pathogens in liquid and dewatered sludge. The following methods have been used to achieve pathogen reduction beyond that attained by stabilization (Tchobanoglous and Burton, 1991):

- Pasteurization
- Other thermal processes such as heat conditioning (see chapter 6), heat treatment (see section 6.2), incineration (see section 10.5), pyrolysis (see section 10.2), or starved air combustion
- High pH treatment, typically with lime, at a pH higher than 12.0 for 3 hours
- Long term storage of liquid digested sludge
- Complete composting at temperatures above 55°C and curing in a stockpile for at least 30 days (see section *8.3*)
- Addition of chlorine to stabilize and disinfect sludge
- Disinfection with other chemicals
- Disinfection by higher-energy irradiation

As indicated in chapter 5, some stabilization processes will also provide disinfection. These processes include lime stabilization, heat treatment, anaerobic digestion, and aerobic digestion (Tchobanoglous and Burton, 1991).

8.1 PASTERUIZATION

Pasteurization is widely used in Europe and required at certain of the countries to disinfect sludge spread on pastures during the spring and summer growing season. For the disinfection of wet sludge, pasteurization at 70°C for 30 minutes will inactivate parasitic ova and cysts. Based on European experience heat pasteurization is a proven technology, requiring skills such as boiler operation and the understanding of high-temperature and pressure processes. The two methods that are used for pasteurizing liquid sludge involve the direct injection of steam, and indirect heat exchange. Because heat exchangers tend to scale or become fouled with organic matter, it appears that steam injection is the most feasible method. Aerobic digestion coupled with anaerobic digestion may also be used for the pasteurization of sludge (see chapter 5) (Tchobanoglous and Burton, 1991).

8.2 LONG-TERM STORAGE

Liquid digested sludge is normally stored in earthen lagoons. Storage is often necessary in land application systems to retain sludge during periods when it cannot be applied because of weather or crop considerations. In this case, the storage facilities can perform a dual function by providing disinfection as well as storage. Typical detention times for disinfection are 60 days at 20°C and 120 days at 4°C (Tchobanoglous and Burton, 1991).

8.3 COMPOSTING

Composting is a sludge waste treatment process used in varying degrees of sophistication in all countries. Traditionally, it intended to be a low-cost process with most applications being for single and low-density development. It has not in the past been attractive for large urban wastewater sludge processing. However, composting has received increased attention as a cost effective and environmentally sound alternate for the stabilization and ultimate disposal of wastewater sludge. Increasingly stringent air pollution regulations and sludge disposal requirements coupled with the anticipated shortage of available landfills have also accelerated the development of composting as a viable sludge management option (Tchobanoglous and Burton, 1991). However, for most likely success, high-technology innovative processes must be developed to produce a product that will sell, is not offensive (malodorous) and does not contain pathogens nor is in the heavy metals. A key disadvantage is that aerobic composting is a “net” importer of energy and anaerobic digestion is a “net” exporter of energy (Kiely, 1997). Much progress has been achieved in recent years in defining sludge and compost characteristics, and as such, areas in South Africa, Australia, the United States and Europe have invested significantly in full-scale composting facilities (Kiely, 1997).

Composting is a “dry” process, whereas anaerobic and aerobic digestion is “wet” process. It is a process in which organic material undergoes biological degradation to a stable end product. A properly composted sludge may be used as a soil conditioner in agricultural or horticultural applications for final disposal, subject to any limitations based on constituents in the sludge (Tchobanoglous and Burton, 1991). Sludge that has been composted properly is a sanitary nuisance-free, humus-like material. Approximately 20 to 30 percent of the volatile solids are converted to carbon dioxide and water. Although composting may be accomplished under aerobic or anaerobic conditions, aerobic composting is used for essentially all municipal wastewater sludge applications (Kiely, 1997).

Aerobic decomposition occurs naturally in soils and composting artificially creates the “soil” environment so as to accelerate the organic decomposition, resulting in the higher rise in temperature necessary for pathogen destruction. Aerobic composting also minimizes the potential for nuisance odors (Tchobanoglous and Burton, 1991). The process of composting takes about 30 days for complete degradation. If degradation is complete the process is irreversible and the end product compost is “fully” stabilized. However, the reality around the world today is that not all composting facilities produce “fully” stabilized product and may not meet the standards for pathogen reduction/elimination (Kiely, 1997).

The composting process involves the complex destruction of organic material coupled with the production of humic acid to produce a stabilized and product. The microorganisms involved fall into three major categories: bacteria, actinomycetes, and fungi. Bacterial activity is responsible for the decomposition of proteins, lipids, and fats at thermophilic temperatures, as well as for much of the heat energy produced. Fungi and actinomycetes are also present at varying levels during the mesophilic and thermophilc stages of composting and appear to be responsible for the destruction of complex organics and the cellulose supplied in the form of amendments or bulking agents (Tchobanoglous and Burton, 1991).

During the composting process, three separate stages of activity and associated temperatures are observed: mesophilic, thermophilic, and cooling. In the initial mesophilic stage, the temperature in the compost pile increases from ambient to approximately 40°C with the appearance of fungi and acid-producing bacteria. As the temperature in the composting mass increases to the thermophilic range, 40 to 70°C, these microorganisms are replaced by thermophilic bacteria, actinomycetes, and thermophilic fungi. It is in the thermophilic temperature range that the maximum degradation and stabilization of organic material occurs. The cooling stage is characterized by a reduction in microbial activity and the replacement of thermophilic organisms with mesophilic bacteria and fungi. During the cooling period, further evaporative release of water from the composted material will occur, as well as stabilization of pH and completion of humic acid formation (Tchobanoglous and Burton, 1991).

Operational temperatures thus range from 40 to 70 °C. If the temperature is too low, the process time increases and pathogens are less likely to be killed. Temperatures above 70 °C may inhabit the composting microorganisms (Kiely, 1997). Aeration is thus required not only to supply oxygen, but to control the composting temperature and remove excess moisture (Tchobanoglous and Burton, 1991). Most composting operations consists of the following steps:

- Mixing dewatered sludge with an amendment and/or a bulking agent
- Aerating the compost pile either by the addition of air, by mechanical turning, or by both
- Recovery of the bulking agent
- Further curing and storage
- Final disposal

An amendment is an organic material added to the feed substrate, primarily to reduce the bulk weight and increase the air voids for proper aeration. Amendments can also be used to increase the quantity of degradable organics in the mixture. Commonly used amendments are sawdust, straw, recycled compost, and rice hulls. A bulking agent is an organic or inorganic material used to provide structural support and to increase the porosity of the mixture for effective aeration. Wood chips are the most commonly used bulking agents (approximately 3 part chips to 1 part sludge), and can be recovered and reused by screening after about 20 to 30 days. This is possible as the chips are about 25mm minimum dimension, whereas the true compost is less than a few millimeters. The moisture content of dewatered sludge ranges from 70 to 80 percent. When blended with chips the moisture content reduces to 40 to 50 percent. At this level, there is sufficient air space to retain the aerobic environment. It follows that if the moisture levels are too high, a risk exists of producing an anaerobic environment. Further, chips are unlikely to be contributing to the metal or pathogen levels (Kiely, 1997).

Odor is not a problem in well-aerated, well-managed systems. The problem with odor from the composting process is due to ammonia, hydrogen sulphide and organic sulphide compounds. Technologies are now readily available to reduce these. For instance, ammonia gas can be stripped in absorption towers through dilute solutions of sulphuric acid. Hydrogen sulfide and organic sulphide can be removed by their absorption in alkaline, oxidizing solution that converts these compounds into non-odorous forms. The major concern for composting is pathogens (Kiely, 1997).

9. HEAT DRYING

The pre-treatment involves thickening (see chapter 4), anaerobic digestion (see chapter 5), sludge conditioning (see chapter 6) and dewatering (see chapter 7) to approximately 25 percent DS. The biogas from the anaerobic digestion can be used as heat supply to the dryer.

Sludge drying involves reducing water content by vaporization of water to the air. The purpose of heat drying is to remove the moisture from the wet-sludge so that it can be incinerated efficiently or processed into fertilizer. Drying is necessary in fertilizer manufacturing so as to perm the grinding of the sludge, to reduce its weight, and to prevent continued biological action (Technobanglous and Burton, 1991).

The result of heat drying is a dried product of approximately 90 to 95 percent DS and pathogen free, typically in the form of granules. Conduction, convection and/or radiation are used in heat transfer in thermal drying. Conditions for effective heat transfer to sludge are (Kiely, 1997):

- A large surface area between the sludge and the thermal carrier (condensing stream, hot air, combustion gases, superheated water or thermal oil)
- A high heat content of the thermal carrier (about 250 to 500 °C gases in rotary dryer)
- A long contact time between the sludge and the thermal carrier (about 30 min in rotary dryer)

The heat drying technologies include (Kiely, 1997):

- Flash dryer
- Rotary dryer
- Fluid bed dryer
- Disc dryer
- Multiple effect evaporator (using oil)

There are two methods of sludge drying; direct drying and indirect drying. In direct drying, the sludge is in direct contact with the drying medium, hot air or gas. The water vapour coming from the sludge leaves the dryer with the drying medium. The latter flows in the same direction as the sludge as it not only dries the sludge but also convey it. Hot air or gas temperatures are in the range 350 to 600 °C, which reduces to 80 to 150 °C after drying. This method is considered simple, but heat-drying medium becomes contaminated with malodorous compounds and so has to be gas scrubbed before re-circulating, possibly with a modern biofilter. As its name implies, in indirect drying there is no contact between the heating medium and the sludge. The disc dryer is one such case. The party wall between the sludge and heating medium is at a temperature of 150 to 250 °C. The heating medium and the sludge water vapour leave the dryer via different routs (Kiely, 1997).

10. THERMAL REDUCTION

Thermal reduction of sludge involves:

- the total or partial conversion of organic solids to oxidized end products, primarily carbon dioxide and water, by incineration or wet air oxidation or,
- the partial oxidation and volatilization of organic solids by pyrolysis or starved-air combustion to end products with energy content.
- The major advantages of thermal reduction are
- maximum volume reduction, thereby lessening the disposal requirements,
- destruction of pathogens and toxic compounds, and
- energy recovery potential
- Disadvantages cited include
- high capital and operating cost
- highly skilled operating and maintenance staffs are required
- the residuals produced (air emissions and ash) may have adverse environmental effects, and
- disposal of residuals, which may be classified as hazardous wastes, may be uncertain and expensive.

Thermal reduction processes are used most commonly by medium to large sized plants with limited ultimate disposal options. It is normally unnecessary to stabilize sludge before incineration. In fact, such practice may be detrimental because stabilization, specifically aerobic and anaerobic digestion, decrease the volatile content of the sludge and consequently increases the requirement for an auxiliary fuel (see section 5.2 and 5.3). Sludge may be subjected to thermal reduction separately or in combination with municipal solid wastes (Tchobanoglous and Burton, 1991). The thermal reduction processes considered in the following discussion include complete combustion, pyrolysis, starved air combustion, wet combustion and sludge melting. Also incineration processes like multiple hearth incineration, fluidized-bed incineration, co-incineration, and wet-air oxidation are discussed.

Thermal reduction methods for wastewater sludge have the potential to be significant contributors to air pollution. Air contaminants associated with thermal reduction can be divided into two categories; odors and combustion emissions. Odors are particularly offensive to the human senses and special attention is required to minimize nuisance odor emissions. Combustion emissions vary depending upon the type of thermal reduction technology employed and the nature of the sludge and auxiliary fuel used in the combustion process. Combustion emissions of particular concern are particulates, oxides of nitrogen, acid gases, and specific constituents such as hydrocarbons and heavy metals (Tchobanoglous and Burton, 1991). Significant advantages in incineration technology have led to decrease air pollution emissions. Successful technologies for particulates collection and gaseous entrapment are all now possible (Kiely, 1997).

10.1 COMPLETE COMBUSTION

The predominant elements in the carbohydrates, fats, and proteins that compose the volatile matter of sludge are carbon, oxygen, hydrogen, and nitrogen (C-O-H-N). Oxygen requirements for complete combustion of a material may be determined from a knowledge of its constituents, assuming that carbon and hydrogen are oxidized to the ultimate and products; carbon dioxide and water (Tchobanoglous and Burton, 1991).

10.2 PYROLYSIS

Because most organic substances are thermally unstable, they can, upon heating in an oxygen free atmosphere, be split through a combination of thermal cracking and condensation reactions into gaseous, liquid, and solid fractions. Pyrolysis is the term used to describe the process (Tchobanoglous and Burton, 1991). In contrast to the combustion process, which is highly exothermic, the pyrolytic process is highly endothermic. Pyrolysis produces (Kiely, 1997):

- a gas stream containing H, CH_4, CO, CO_2 and others, depending on the sludge
- an oil/tar stream
- a char of almost pure carbon

Two forms of pyrolysis under research for sludge are oil from sludge (OFS) and gasification. In the OFS process, the organics in the sewage (pre-dried to at least 95 percent DS) are converted to a liquid fuel, not unlike fuel oil. The principal piece of technology is the conversion reactor. Firstly, the dried sludge (> 25 percent DS) is heated to approximately 450 °C without oxygen. Under these conditions, about half of the sludge is vaporized. These vapors are contracted with the tar residue of the sludge and aliphatic hydrocarbons are produced. The process produces oil and char, non-condensable gas and water. It is possible to combust these by-products at above 800 °C to produce energy for drying (Kiely, 1997).

Gasification involves taking dried sludge (> 80 percent DS) and converting it into a clean combustible gas, which may be converted to electricity or hot water for district heating. The main component of the system is a gasification reactor. The dried sludge (in briquette form) is fed to the reactor and with air is heated to 500 °C in the distillation zone and then to 800 °C in the carbonization zone. As the amount of the air is controlled, the solids give off their gases without combustion. The gases then pass through a core with temperatures above 1200 °C, where they are cleaned of tars and oils. The two products of gasification are gas and ash (Kiely, 1997).

10.3 STARVED AIR COMBUSTOION

Starved air combustion combines some of the features of complete combustion with pyrolysis. The process is easier to control than pyrolysis and provide better control of air emissions than complete combustion. Products of the starved air combustion process are combustible gases, tars, oils, and a solid char that can have appreichiable heating value (Tchobanoglous and Burton, 1991).

10.4 WET COMNUSTION

Organic substances may be oxidized under high pressures at elevated temperatures with the sludge in a liquid state by feeding compressed air into the pressure vessel. The process is used for the oxidation of untreated wastewater sludge pumped directly from the primary settling tank or thickener. Combustion is not complete; the average is 80 to 90 percent completion. Thus, some organic matter, plus ammonia, will be observed in the end products (Tchobanoglous and Burton, 1991).

10.5 INCINERATION

Incineration of sewage sludge is a technical option used to some extent by most developed countries and is an integral part of the treatment policies on sludge (Kiely, 1997). For sewage sludge, fluidized beds, multiple hearth incinerations, co-incineration and wet air oxidation are all used (Tchobanoglous and Burton, 1991).

Generally, sewage sludge is first dewatered and can be burned with auxiliary fuel at 20 to 30 percent DS. At dried cake values of 30 to 50 percent DS, sludge will burn unaided. Incineration of sludge is the high-temperature combustion (> 900 °C) of the combustible sludge elements – carbon, hydrogen and sulphur in addition to those grease, carbohydrates and proteins. The end products of the combustion of sludge with excess air are carbon dioxide, sulfur dioxide and water vapor. Ash is also produced. The volume is reduced to about 15 percent of it original value (Kiely, 1997).

10.5.1 Multiple Heart Incineration

Multiple heart incineration is used to convert dewatered sludge cake to an inert ash. The process is complex and requires specially trained operators. Sludge cake is fed onto the top hearth and slowly raked to the center. From the center, sludge cake drops to the second hearth where the rakes move it to the periphery. The sludge cake drops to the third hearth and is again raked to the center. The hottest temperatures are on the middle hearths, where the sludge burns and where auxiliary fuel is also burned as necessary to warm up the furnace and to sustain combustion. Preheated air is admitted to the lowest hearth and is further heated by the sludge as the air rises past the middle hearths where combustion is occurring. The air then cools as it gives up its heat to dry the incoming sludge on the top hearth. Under proper operating conditions, particulate discharges to the air from wet scrubbers are less than $0.65 kg/10^3$ of dry sludge input (Tchobanoglous and Burton, 1991).

10.5.2 Fluidized Bed Incineration

The fluidized bed incinerator commonly used for sludge incineration is a vertical, cylindrically shaped refractory-lined steel shell that contains a sand bed (media) and fluidizing air orifices to produce and sustain combustion. The sand bed support area contains orifices, called ”tuyeres”, through which air is injected in the incinerator at a pressure of 20 to 35 kN/m^2, to fluidize the bed. The main bed of suspended particles remains at a certain elevation in the combustion chamber and “boils” in place. Units that function in this manner are called “bubbling bed” incinerators. The mass of suspended solids and gas, when active and at operating temperature expands to about double the at-rest volume. Sludge is mixed quickly within the fluidized bed by the turbulent action of the bed. Evaporation of the water and combustion of the sludge solids takes place rapidly. Combustion gases and ash leave the bed and are transported through the freeboard area to the gas outlet through the top of the incinerator. Particulates and other air emissions are comparable to those from the multiple hearth incinerator (Tchobanoglous and Burton, 1991).

10.5.3 Co-incineration

Co-incineration is the process of incinerating wastewater sludge with municipal solid wastes. The major objective is to reduce the combined costs of incinerating sludge and solid wastes. The process has the advantages of producing the heat energy necessary to evaporate water from sludge, supporting the combustion of solid wastes and sludge, and providing an excess of heat for steam generation. A water-filled boiler serves as the furnace for these fuels. The steam output from the boiler is used to clean the exhaust gases (Tchobanoglous and Burton, 1991). There are examples of sludge incinerators in co-disposal arrangements as follows (Kiely, 1997):

- Incineration of sludge only
- Incineration of sludge + solid waste
- Incineration of sludge + bark waste
- Various other combinations

10.5.4 Wet-Air Oxidation

The process is the same as discussed under heat treatment (see section 6.2), except that higher pressures and temperatures are required to oxidize the volatile solids more completely (Tchobanoglous and Burton, 1991). Wet air oxidation is a process whereby the sludge organic solids are stabilized in an aerobic, high-pressure, high-temperature environment. It is a liquid phase reaction between the organic material in water and oxygen. The objective of wet air oxidation of sludge is to oxidize a large part of the organic sludge components, leaving an almost inorganic sludge, which can readily be dewatered. In contrast to most forms of sludge treatment, the process of wet air oxidation does not require the sludge to be dewatered. Pre-treatment is adequate if the sludge is thickened to approximately 5 percent DS (Kiely, 1997).

Untreated sludge is grained and mixed with a specified quantity of compressed air. The mixture is pumped through a series of heat exchangers and then enters a reactor, which is pressurized to keep the water in the liquid phase at the reactor operating temperature of 175 to 315°C (Tchobanoglous and Burton, 1991) and pressures of approximately 10 MPa (Kiely, 1997). Gases, liquid, and ash leave the reactor. The liquid and ash are returned through heat exchangers to heat the incoming sludge and then pass out of the system through a pressure-reducing valve. Gases reduced by the pressure drop are separated in a cyclone and released to the atmosphere. A major disadvantage associated with this process is the high strength recycle liquor produced. The liquors represent considerable organic load on the treatment system (Tchobanoglous and Burton, 1991).

10.5.5 Sludge melting

This process is a comparable to incineration. Organic sludge are reduced to about one-thirteen of their original volume by incineration and to about one-thirtieth by the melting process. Melting involves several steps, including (Kiely, 1997):

- Pre-treatment, i.e. dewatering
- Melting
- Heat recovery
- Waste gas purification
- Slag production

In the melting stage, the sludge is heated to above 1200 °C to evaporate the water and to thermally decompose and melt the inorganic components. After melting, molten inorganic materials are converted to beneficial end products, e.g. slag. The characteristics of the final slag will depend on the cooling method used. Rapid cooling produces a vitreous low-strength slag, while slow cooling produces a high –strength slag. The types of melting technologies include (Kiely, 1997):

- Cake bed melting furnace
- Reflector melting furnace
- Cyclone melting furnace

11. ULTIMATE DISPOSAL

The beneficial use of sludge is receiving considerable attention because of the decline in available landfill and the interest in using the beneficial nutrient and soil conditioning properties of sludge. In addition to the benefits of land application, sludge may be distributed and marketed for residential and commercial uses as a soil amendment and conditioner. Sludge may also be treated chemically to stabilize the sludge for use as landfill cover or for landscaping or land reclamation projects (Tchobanoglous and Burton, 1991).

Final disposal for the sludge and solids that are not beneficially used usually involves some form of land disposal. In addition to spreading sludge on land, other methods of final disposal include landfilling and lagooning. As in the case of land application of sludge, the regulations for other methods of sludge disposal are becoming increasingly stringent and require close attention and review (Tchobanoglous and Burton, 1991). This section discusses:

- Land application of sludge
- Landfilling
- Lagooning
- Chemical fixation
- Distribution and marketing
- Ocean dumping

11.1 LAND APPLICATION OF SLUDGE

Land application of wastewater sludge has been practiced for many years, modern applications being limited to digested sludge. The nutrient value of the sludge is beneficial to vegetation, and its granular nature may serve as soil conditioner (Donald et al, 1995). The interest in land application of sludge has increased in recent years as the availability and feasibility of other sludge management options such as landfilling (see section 11.4), incineration, and ocean dumping (see section 11.6) have decreased. Land application of stabilized municipal wastewater sludge is defined as the spreading of sludge on or just below the soil surface. Land application is currently the most widely employed sludge use and disposal option among small- and medium-sized treatment plants in the United States (Tchobanoglous and Burton, 1991).

Sludge disposal is greatly facilitated by volume reduction through dewatering may be accomplished by mechanical means such as centrifugation, vacuum filtration, filter pressing, or by air drying as described in chapter 7 (Donald *et al*, 1995). Table 10 (see chapter 7) shows the approximate solids content of dewatered sludge depending on the dewatering method that has been used. Sludge may be applied to

- agricultural land,
- forestland,
- disturbed land (including re-vegetation), and
- dedicated land disposal sites (see section 11.4).

In all four cases, the land application is designed with the objective of providing further sludge treatment. Sunlight, soil microorganisms, and desiccation combine to destroy pathogens and many toxic organic substances found in sludge. Trace metals are trapped in the soil matrix and nutrients are taken up by plants and converted to useful biomass. In the first three cases, sludge is used as a valuable resource to improve the characteristics of the land. Sludge acts as a soil conditioner to facilitate nutrient transport, increase water retention, and improve soil tilth. Sludge also serves as a partial replacement for expensive chemical fertilizers.

11.1.1 Land spreading in forestland.

Land spreading in forestland is not always within an economic travel distance of urban wastewater treatment plants. Another difficulty is the mechanics of obtaining an even spread of sludge due to the frequent interruptions by the presence of trees. The methodology of spreading is by spray gun and this can also damage the bark of trees if the force is too strong. Besides the technical difficulties associated with actual spreading and the cost implications of transport, other constrains are related to sludge constituents, including pathogens, and nitrate leaching (Kiely, 1997). Accelerated tree growth (200 to 300 percent) can result from the application of sludge. This cause will change the characteristic of the wood in relation to moisture content, structural properties, etc. (Kiely, 1997).

Disturbed Land

Land in many places that has been overgrazed has expended its nutrients, which may be brought back into commission quickly by application of sewage sludge. The conditions for application are in this case more metal limiting than nutrient limited (Kiely, 1997). The application of sewage sludge to re-vegetate mining sites has been going on for several decades. As mining is international practice, the opportunities exist for utilizing large volumes of sludge to restore these landscapes in almost all countries. Difficulties have been encountered with re-vegetation due to low pH of these lands, their low field capacity (unable to hold much water) and the presence of high concentrations of heavy metals (Kiely, 1997). The rates of sludge application to re-vegetate areas is typically one or two times order of magnitude greater than that for sludge applied on cropland. As such, the potential problems are: leaching of nitrogen to groundwater, surface runoff of non-soil-bound metals and pathogen transmission (Kiely, 1997).

The steps involved in the development of a sludge land application system include the following (Tchobanoglous and Burton, 1991):

- Characterization of sludge quantity and quality
- Review of pertinent federal, state, and local regulations
- Evaluation and selection of site and disposal option
- Determination of process design parameters – loading rates, land area requirements, application methods and scheduling.

11.1.2 Sludge characteristics affecting land application

Characteristics of sludge that affect its suitability for land application or affect the design of land application system include organic content (usually measured as volatile solids), nutrients, pathogens, metals, and toxic organics (Tchobanoglous and Burton, 1991).
Organic Content and Pathogens.

Degradable organic material in unstabilized sludge can lead to odor problems and attract vectors (flies, mosquitoes, and rodents) in a land application setting. Pathogens (bacteria, viruses, protozoa, and eggs of parasitic worms) are concentrated in sludge and can spread diseases if there is human exposure to the sludge. To meet prescribed limits, organic content and pathogens must be reduced significantly prior to land application by means of pre-application treatment processes (Tchobanoglous and Burton, 1991).

Nutrients

Major plant nutrients – nitrogen, phosphorous, and potassium- are not removed substantially during sludge processing but are taken up by vegetation after sludge has been applied to the land. Nitrogen is normally the nutrient of concern in land application because of the potential for nitrate contamination of groundwater. The nitrogen uptake rate of vegetation, therefore, is a key design parameter in determining sludge loading rates. When nutrient content of wastewater sludge is compared to commercial fertilizers (see table 11), sludge can meet only a portion of the complete nutrient needs of plants in most cases (Tchobanoglous and Burton, 1991). The major nutrient not provided in significant quantities by sludge is potassium (Kiely, 1997).

Table 11 Comparison of nutrient levels in commercial fertilizers and wastewater sludge (Tchobanoglous and Burton, 1991).

	Nutrients, %		
	Nitrogen	Phosphorous	Potassium
Fertilizers for typical agricultural use	5	10	10
Typical values for stabilized wastewater sludge	3.3	2.3	0.3

Metals and organics

Wastewater sludge contains trace metals and organic compounds that are retained in the soil and pose potential toxic risk to plants, animals, and humans. The principal metal of concern is cadmium because it can accumulate in plants to levels that are toxic to humans and animals but below levels that is toxic to plants (phytotoxic). Because of the potential wide range of constituents concentrations found in various sludge, such as those reported in table 12, a thorough characterization of sludge is necessary when land application of sludge is considered. Wastewater sludge also contains organic compounds, primarily chlorinated hydrocarbons such as PCBs, which are slow to degrade in the soil profile. The principal concern with such organics is not with plant uptake, which does not occur, but with the direct ingestion of compounds by animals, particularly dairy cattle grazing on sludge treated grasses. There is also evidence that organics can be absorbed onto the surface of root crops such as carrots. Consequently, loading times for specific organic compounds are of concern when designing land application systems for sludge (Tchobanoglous and Burton, 1991).

Table 12 Typical metal content in wastewater sludge (Tchobanoglous and Burton, 1991).

	Dry sludge, mg/kg	
Metal	Range	Median
Cadmium	1-3.410	10
Chromium	10-99.000	500
Copper	84-17.000	800
Lead	13-26.000	500
Mercury	0.6-56	6
Nickel	2-5.300	80
Zinc	101-49.000	1700

11.1.3 Site evaluation and selection.

Typical sludge loading rates given in table 13 may be used to develop preliminary estimates of land area requirements. Physical site characteristics of concern include topography, soil permeability, site drainage, depth to groundwater, subsurface geology, proximity to critical areas, and accessibility (Tchobanoglous and Burton, 1991).

Table 13 Typical sludge application rates for various land disposal options (Tchobanoglous and Burton, 1991).

Land disposal option	Time period of application	Application rates tons/acre (x2.2417 Mg/ha) (Dry Solids)	
		Range	Typical
Agriculture use	Annual	1-30	5
Forest	One time or at 3- to 5-year intervals	4-100	20
Land reclamation	One time	3-200	50
Dedicated disposal site	Annual	100-400	150

Topography.

Topography is important as it affects the potential for erosion and runoff applied sludge for equipment operability. Recommended slope limitations as related to sludge application methods are presented in table 14 (Tchobanoglous and Burton, 1991).

Table 14 Typical slope limitations for land application of sludge (Tchobanoglous and Burton, 1991).

Slope, %	Comment
0-3	Ideal; no concern for runoff or erosion of liquid sludge or dewatered sludge.
3-6	Acceptable; slight risk of erosion; surface application of liquid or dewatered sludge is acceptable.
6-12	Injection of liquid sludge required for general cases, except in closed drainage basin and/or when extensive run-off control; surface application of dewatered sludge is usually acceptable.
12-15	No application of liquid sludge should be made without extensive run-off control; surface application of dewatered sludge is acceptable, but immediate incorporation into the soil is recommended.
Over 15	Slopes greater than 15% are suitable only for sites with good permeability where the length of slope is short and where the area with a steep slope is a minor part of the total land application area.

Soil.

In general, desirable soils have moderately slow permeabilities, 0.5 to 1.5cm/h, are well drained to moderately well-drained, are alkaline or neutral (pH>6.5) so as to control metal solubility, and are deep and relatively fine textured for high moisture and nutrient holding capacity. With proper design and operation, almost any soil may be suitable for sludge application (Tchobanoglous and Burton, 1991).

Soil depth to groundwater

A basic philosophy inherent in federal and state regulations is to design sludge application systems based on sound agronomic principles so that sludge application poses no greater threat to groundwater than current agricultural practices. Because the groundwater fluctuates on a seasonal basis in many soils, difficulties are encountered in establishing an acceptable minimum depth to groundwater. The quality of the underlying groundwater and the sludge application option has to be considered. Generally, the greater the depth to the water table, the more desirable a site is for sludge application. Typical minimum depths for various sludge application options are listed in table 15 (Tchobanoglous and Burton, 1991).

Table 35 Typical minimum depth to groundwater for land application of sludge (Tchobanoglous and Burton, 1991).

Type of site	Drinking water aquifer, ft (ftx0.3048 m)	Excluded aquifer, ft (x0.3048 m)
Agricultural	3	1.5
Forest	6*	2
Drastically disturbed land	3**	1.5
Dedicated land disposal	>3	1.5

*Seasonal (springtime) high water and/or perched water less than 3 ft is not usually a concern.

** Assumes no groundwater contact with leachate from sludge application operation.

11.1.4 Application methods

Land application of wastewater sludge has been limited to ground use for forage crops for non-human consumption, although the possibility of its use on ground to grow edible produce is still being investigated. Metal toxicity in plants and water pollution from excess nitrates appears to be the limiting factors in land application of sludge (Donald et al, 1995). However, the application rate for sludge is typically designed for either the N or P levels of the crop grown on a particular soil. The general approach for determining application rates are (Kiely, 1997):

- Nutrient crop requirement, taking account of carry-cover from previous years
- N crop needs, Cd limitation and P crop needs.

Sludge application is terminated when cumulative metal limits are reached. The methods of sludge application selected will as mentioned before depend on the physical characteristics of the sludge (liquid or dewatered), site topography, and the type of vegetation present (annual field crops, existing forage crops, trees or planted land) (Tchobanoglous and Burton, 1991).

Liquid Storage Application

Application of sludge in the liquid state is attractive because of its simplicity. Dewatering processes are not required, and the liquid sludge can be transferred by pumping. Typical solids concentrations of liquid sludge applied to land range from 1 to 10 percent. Liquid sludge may be applied to land by vehicle or by irrigation methods similar to those used for wastewater distribution. Limitations to vehicular application include limited tractability on wet soil and potential reduction in crop yields due to soil compaction from truck traffic. Surface distribution may be accomplished by tank trucks or tank wagons equipped with rear-mounted spreading manifolds or by tank trucks mounted with high capacity spray nozzles or guns. Specially designed, all-terrain, sludge application vehicles with spray guns is ideally suited for sludge application on forestlands. Vehicular surface application is the most common method used for field and forage croplands. The procedure used commonly for annual crops is to

- spread the sludge prior to planting
- allow the sludge to dry partially, and
- incorporate the sludge by disking or plowing.

The process is then repeated after harvest (Tchobanoglous and Burton, 1991). Liquid sludge can be injected below the soil surface by using tank wagons or tank trucks with injection shanks, or it can be incorporated immediately after the surface application by using plows or discs equipped with sludge distribution manifolds and covering spoons. Important advantages of injection or immediate incorporation methods include:

- minimization of potential odors and vector attraction,
- minimization of ammonia loss due to volatilization,
- elimination of surface runoff, and
- minimum visibility leading to better public acceptance.

Sprinkling has been used mainly for application to forested lands and occasionally for application to dedicated disposal sites that are relatively isolated from public view and access. Sprinklers can operate satisfactory on land too rough or wet for tank trucks or injection equipment and can be used throughout the growing season. Disadvantages to springkling include power costs of high-pressure pumps, contact of sludge with all parts of the crop, possible foliage damage to sensitive crops, potential odors and vector attraction problems, and potentially high visibility to public (Donald *et al*, 1995). Furrow irrigation can be used to apply sludge to row crops during the growing season. Disadvantages associated with furrow irrigation are localized settling of solids and the potential of sludge in the furrows, both of which can result in odor problems (Tchobanoglous and Burton, 1991).

Dewatered sludge application

Application of dewatered sludge to the land is similar to an application of semisolid animal manure. Typical solids concentrations of dewatered sludge applied to land range from 15 to 30 percent. Application of sludge using conventional manure spreaders is an important advantage of dewatered sludge because private farmers can apply sludge on their lands with their own equipment (Donald *et al*, 1995). Other advantages include reduced sludge hauling, storing and spreading costs. For forestland application where use of dewatered sludge is often impractical, sludge may be dewatered for storage and hauling and re-liquefied to allow spray application (Tchobanoglous and Burton, 1991).

11.2 DISTIBUTING AMD MARKETING

Sludge that is distributed and marketed is used as a substitute to topsoil and peat on lawns, golf courses, and parks and in ornamental and vegetable gardens. Usually the sludge used for these purposes are composted. The sludge may be distributed in bulk or in bags. Application rates of sludge may be limited based on whether it is used for food or nonfood crops (Tchobanoglous and Burton, 1991).

11.3 CHEMICAL FIXATION

The chemical fixation/solidification process has been applied to the treatment of industrial sludge and hazardous wastes to immobilize the undesirable constituents. The process has also been used to stabilize municipal sludge for use as landfill cover and for land reclamation projects. Stabilized sludge may also be disposed of in landfills. The chemical fixation process consists of mixing untreated or treated liquid or dewatered sludge with stabilizing agents such as cement, sodium silicate, pozzolan (fine grained silicate), and lime so as to chemically react with or encapsulate the sludge. The process may generate a product with high pH, which inactivates the pathogenic bacteria and viruses (Tchobanoglous and Burton, 1991).

11.4 LANDFILLING

A sanitary landfill can be used for disposal of sludge, grease, grit, and other solids. Dewatering of sludge is usually required to reduce the volume to be transported and to control the generation of leachate from the landfill. In many cases, solids concentration is an important factor in determining the acceptability of sludge in landfills. The sanitary landfill method is most suitable if it is also used for disposal of other solid wastes of the community; co-disposal landfill. The requirements for such landfills include (Kiely, 1997):

- A dry solid sludge content >35 percent
- A sludge shear strength >10 kN/m^2
- A mass of municipal waste/sludge ratio of >10:1

In a co-disposal landfill sludge is dumped at the tip of the landfill face and spread in a layer less than 0.25 m thick. Municipal waste is spread from the top of the landfill face, covering the sludge with a >1 m tick layer of municipal waste. The environmental aspects of co-disposal landfills includes (Kiely, 1997):

- Significant reduced chemical oxygen demand (COD) values for leachate
- Reduced VFA values in leachate
- Increased pH values in leachate from about 6.0 to 7.5
- Increased methane (CH_4) production

In a true sanitary landfill, the wastes are deposited in a designate area, compacted in place, and covered with a 30cm layer of clean soil. In some landfills, composted sludge and chemically treated sludge have been used as cover material. Composted sludge also serves to reduce odors that might emanate from disposal of municipal solid wastes. In sludge monofills, the regulations may require daily or more frequent covering for vector control and may include limitations on methane gas generation (Tchobanoglous and Burton, 1991).
Selecting a land disposal site must consider

- environmentally sensitive areas such as wetlands, flood plains, recharge zones for aquifers, and habitat for endangered species
- runoff control to surface water
- groundwater protection
- air pollution from dust, particulates and odors
- disease vectors, and
- safety as related to toxic materials, fires and access.

After several years, during which the wastes are decomposed and compacted, the land may be used for recreational or other purposes for which gradual subsidence would not be objectionable (Tchobanoglous and Burton, 1991).

11.5 LAGOONING

Lagooning of sludge is another common disposal method because it is simple and economical if the treatment plant is in a remote location. Sludge may be stored indefinitely in a lagoon, or it may be removed periodically after draining and drying. A lagoon is an earth basin into which untreated or digested sludge is deposited. In untreated sludge lagoons, the organic solids are stabilized by anaerobic and aerobic decomposition, which may give rise to objectionable odors. The stabilized solids settle to the bottom of the lagoon and accumulate. If the lagoon is used only for digested sludge, the nuisances mentioned should not be a problem (Tchobanoglous and Burton, 1991).

11.6 OCEAN DUMPING

Ocean dumping of sewage sludge has been most common for island countries and urban areas on the cost; *e.g.* New York, Los Angeles, London, Tokyo, etc, all disposed most of their sludge out into seas. The Helsinki Agreement however, was signed by most countries to eliminate ocean dumping by 1998. The Helsinki Agreement has been added into the EU Directive on urban wastewater as of 31 December, 1998 (Kiely, 1997).

12. METALS

As mentioned in section 11.2 sludge contain trace metals that pose potential risk to plants, animals and humans. The main source for metals in sewage sludge is through the sewage system as the system receives domestic wastewater, urban runoff and industrial discharge. Certain metals such as Fe may also be added during wastewater treatment (see section 6.1). The extent to which industrial discharge and storm water enter the system is critical for metal concentrations, particularly for metals such as lead that usually enters the system with runoff and with chromium and nickel that mostly comes from industrial sources. However, domestic wastewater itself is also a significant source of certain metals, for example copper and zinc (Chino, 1991). Elevated levels of mercury can be found in sewage sludge, but is not discussed further in this study since the concentration of mercury is hard to determined with the analysis methods used.

12.1 HEAVY METALS

Typical heavy metal content in wastewater sludge is shown in table 12. The main toxic metals found in sewage sludge include heavy metals such as:

- Cadmium (Cd)
- Chromium (Cr)
- Copper (Cu)
- Nickel (Ni)
- Lead (Pb)
- Zinc (Zn)

12.1.1 Cadmium

Cd is a highly toxic and non-essential metal (Blom, 2002). For the last 30 years Cd has been used or present in corrosion prevention, polymer stabilization, and electronics (Alloway and Ayres, 1997). Phosphate fertilizer is also one important source of Cd, as well as the production and use of batteries, paints and plastic. In many countries however, the use of Cd in paints and plastics is no longer permitted but these products can still cause problems with e.g. water leaching from waste disposal sites (Ekvall, 1995). Mining and refining of Zn ores is considered to be the major anthropogenic source of Cd emissions worldwide (Elinder, 1986). Cd can accumulate in kidneys of mammals and cause kidney dysfunction (Blom, 2002).

12.1.2 Chromium

Cr is an essential metal, used for carbohydrate metabolism in animals (Alloway and Ayres, 1997). Cr is mostly present in particulate form and adsorbed to particles (Stumm and Morgan, 1996). Mainly the metallurgical and chemical industries consume Cr. It is used in stainless steel production, electroplating and in a variety of chemical products such as pigments, catalysts, wood preservatives and tanning agents. Cr containing phosphate fertilisers are another source (Ekvall, 1995). Cr can occur in the trivalent (chromite) and the hexavalent (chromate) form. There is a difference in the toxicity off Cr(III) and Cr(VI) with the oxidised form being more toxic, Cr(VI) being classified as a human carcinogen. Studies have shown increased lung cancer after exposure to Cr(VI) (Mach *et al*, 1996).

12.1.3 Copper

Cu is an essential metal (Blom, 2002). The Cu content in sewage sludge comes from a variety of sources, some of which are diffuse and difficult to control. Cu pollution can arise from Cu smelting and mining, brass manufacture, and electroplating (Alloway and Ayres, 1997). With increasing control of industrial effluents the contribution from urban runoff in many places has been revealed. Car brake linings release Cu and the corrosion of roofs and drain pipes contribute to the content of urban runoff (Morrison *et al*, 1984). Another important source of Cu is drinking water pipes that corrode and contribute significantly to the sewage Cu content (Ekvall, 1995). The most common health effect of Cu is diarrhoea (Pettersson, 1995).

12.1.4 Nickel

The dominant source of anthropogenic Ni is from dry cell batteries and metallurgical industries. In sewage sludge, Ni may also originate from the coagulant used in wastewater treatment, where it can be found as a contaminant (Ekvall, 1995).

12.1.5 Lead

Most of the atmospheric Pb originates directly from traffic, which make urban runoff an important source of Pb in sludge as it contains particles from car exhaust. Although the introduction of catalytic converters has created an increasing demand for unleaded petrol, it can still take years before the larger fraction of road dust is washed down to the sewer system. Pb containing pesticides and paint are other contributors to Pb concentrations as well as plastic rain gutters that are known to elevate Pb concentrations in roof runoff (Good, 1993). Other sources for Pb pollution certain cosmetic, food cans, ammunition used for shooting birds and pollution from mining and smelting (Alloway and Ayres, 1997). Pb is a non-essential metal. It is toxic but not bio available as many other metals, but can be accumulated in the human bone marrow, where red blood corpuscle formation occurs (Alloway and Ayres, 1997). Exposure of Pb may also lead to kidney damage. Adsorptions of Pb in amounts that are not high enough for acute poisoning are known to induce behaviour abnormalities (Alloway and Ayres, 1997). Alkyl Pb species are organic forms of Pb, previous used as an additive to petrol. It has been found that these compounds can penetrate the skin and biological membranes. They are therefore considered more harmful than inorganic Pb.

12.1.6 Zinc

Mining and smelting are often activities associated with Zn pollution. It is used in galvanized steel and is released into the environment by weathering and corrosion (Alloway and Ayres, 1997). The extended use of galvanized steel makes Zn enter the sewer system through urban runoff, household wastewater and industrial effluents (Ekvall, 1995). Zinc is an essential metal and has relatively low toxicity to animals and humans (Alloway and Ayres, 1997). Studies have shown increased allergies and minor health problems associated with Zn exposure (Ahumada, 1998).

12.2 OTHER METALS

The above mentioned heavy metals are considered the most important metals in sewage sludge and are thus the most studied, but there are also other metals found. The metals that have elevated metal concentrations in sewage sludge due to their presence in the near surrounding are referred to as background metals.

Table 16. Frequent alkali, earth alkali and valence metals found in bedrock (Morrison *et al.*, 2001).

Alkali metals	Alkali earth metals	Valence metals
Na	K	Mn
Mg	Ca	Fe
Al	Ti	Ni
Si		Cu
		Zn

Background metals can be natural and/or anthropogenic. Naturally they can derive from the bedrock at different locations. These are both alkali metals and earth alkali metals. They may also be valence metals that are associated with those metals. Table 16 shows frequent alkali, earth alkali and valence metals found in bedrock (Morrison *et al*, 2001).

Natural background metals differ in concentration depending on location, thus the concentration in sewage sludge varies. Table 17 shows the dominant natural background metals that are commonly present in Sweden and in the study area in South Africa. The metal levels in sewage sludge may, however, be worsened by mining or other anthropogenic activities.

Table 17. Background metals in Sweden.

Metal	Natural cause	Anthropogenic cause
U	bedrock	
Fe		treatment processes
Cu	bedrock	pipe system

Table 18. Background metals in South Africa.

Metal	Natural cause	Anthropogenic cause
Cu	bedrock	
Pt	bedrock	mining
Ni	bedrock	
Ag	bedrock	
Pb		leaded petrol

Anthropogenic background metals may derive from treatment processes, materials used in pipe systems, the use of leaded petrol etc. Examples are; Ag used in photographic processing and Mo used as an additive to stainless steel (Ekvall, 1995). Other metals are atmospheric fallouts such as; Pt used in catalytic converters on automobiles, which has lead to increasing levels of Pt in road dust (Kylander, 2002) that eventually may increase the concentration in sludge. Ti is also present in urban runoff, which is a white pigment used in road paints that wears off the road surface considerably each year (Ekvall 1995). Table 18 shows the anthropogenic background metals found in Sweden and the study area in South Africa.

12.3 GUIDELINES FOR SLUDGE LAND APPLICATION

To ensure the reuse of sludge as fertilizer without jeopardizing human health rules and regulations have been developed. The Swedish Environmental Protection Agency (SEPA) has set up limitations regarding the use of sewage sludge as agricultural fertilizers. These guidelines were based on the hypothesis that there should be no negative effects on land, fauna or to humans through metals during a 1000-years period. Table 19 show the guideline values developed by SEPA for heavy metal concentration in sewage sludge spread on land. Further on in this case study these values will be used when analyzing South African sewage sludge. Limitations regarding the highest amount of metals allowed to be put on farmlands within a 7-years-period have also been developed. These limitations are showed in table 20.

Table 19. Swedish heavy metal guideline values for spreading sewage sludge on farmland (web ref 8).

Metal	*mg/kg TS*
Lead	100
Cadmium	2
Copper	600
Chromium	100
Mercury	2.5
Nickel	50
Zinc	800

Table 20. Maximum amounts of heavy metals aloud to be spread on Swedish farmland (web ref 8).

Metal	*G/ha per year*
Lead	25
Cadmium	0.75
Copper	300
Chromium	40
Mercury	1.5
Nickel	25
Zinc	600

In 1998 25% of all produced sewage sludge was spread on farmland while 9 percent was spread on other land, the rest was placed at waste disposal sites. It is seen that the average heavy metal concentrations generally have been reduced significantly since the 1980s. Levels of Cu are however constant (web ref 8).

Table 21. Heavy metal concentration in soil and potential risks (web ref 8).

Class	*Designation*	*Cd concentration (mg/kg soil)*	*Possible risk*
1	Low level	< 0.2	
2	Average level	0.2 – 0.3	
3	High level	> 0.3	Healthaffecting levels in crop

Class	*Designation*	*Pb concentration (mg/kg soil)*	*Possible risk*
1	Low level	< 15	
2	Average level	15 – 30	
3	High level	> 30	Toxic for vegetation and microorganisms

Class	*Designation*	*Cu concentration (mg/kg soil)*	*Possible risk*
1	Low level	< 20	Shortage for vegetation
2	Average level	20 – 35	
3	High level	> 35	Toxic for vegetation

Class	*Designation*	*Ni concentration (mg/kg soil)*	*Possible risk*
1	Low level	< 10	
2	Average level	10 – 20	
3	High level	> 20	Toxic for vegetation

Class	*Designation*	*Zn concentration (mg/kg soil)*	*Possible risk*
1	Low level	< 50	Shortage for vegetation
2	Average level	50 – 100	
3	High level	> 100	Toxic for vegetation

The levels of heavy metals given in table 21 refer to total concentrations (measured by extraction with nitric acid) in cultivated soil at 0-20 centimeters depth. At deep soil layers heavy metal content can be assumed to be relatively unaffected by contamination and human impact. The concentrations found can thus be used representing an undisturbed state. The relation between the concentration of the topsoil and lower soil has been used to indicate accumulation of metals in the soil due to anthropogenic activities. Table 22 show the metal accumulation in soil due to land application of sludge (web ref 8).

Table 22 Heavy metal accumulation in soil (web ref 8).

Class	Designation
1	No accumulation
2	Moderate accumulation
3	Severe accumulation

13. METHODS OF ANALYSIS

13.1 MICROWAVE DIGESTION

The microwave digestion system is used for digestion, solvent extraction, synthesis and protein hydrolysis. It has pressure and optional temperature control sensors with programmed pressure and temperature detection features. It is the only system with a calibrating sensor that monitors the temperature in every vessel, ensuring save procedure. The high-pressure vessels permit superheating of acid mixtures, resulting in a vast acceleration of the ongoing reactions. The instrument can run 14 vessels at once and ensure complete digestion with the highest temperature or pressure vessels (web ref 9).

13.2 INDUCTIVELY COUPLED PLASMA – MASS SPECTROSCOPY

Inductively Coupled Plasma - Mass Spectroscopy (ICP-MS) is a low detection limit technique for determining most of the elements in the periodic table rapidly. It is advantageous in that it has a multi-element capacity where it is possible to measure up to 75 elements at the same time and very low detection limit of ng l^{-1} and even pg l^{-1} (Barbante *et al.*, 1999 and Jarvis *et al.*, 1992). ICP-MS also covers a wide range of mass numbers and it is possible to measure the isotopes of each element (Jarvis *et al.*, 1992). It is occasionally paired with laser ablation (LA) techniques for the analysis of solids.

13.2.1 ICP-MS principles

The ICP-MS consists of tree major sections; the inductively coupled plasma source, the quadrupole mass spectrometer and the interface linking the two sections (Jarvis *et al.*, 1992). The ICP-MS process can be broken down into 5 main steps; sample introduction, sample ionization, ICP-MS interface, mass discrimination and detection (figure 12).

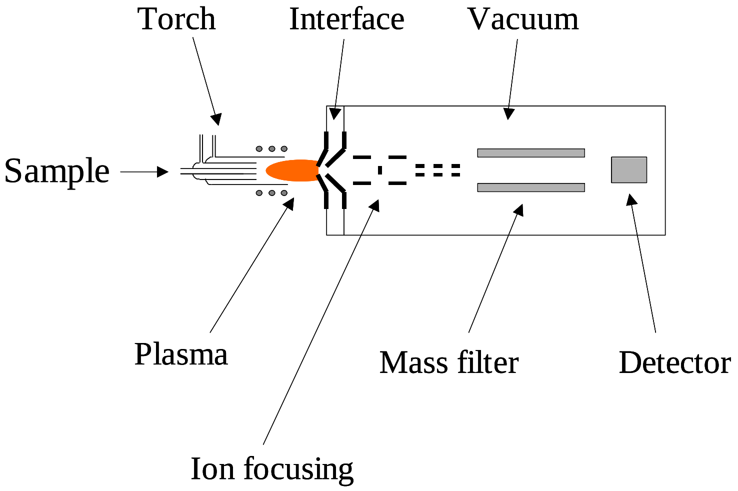

Figure 12. Cross-section of a quadrupole-ICP-MS instrument (Rauch, 2001)

1. Sample introduction

ICP-MS is capable of accepting gas, solids or gas liquid samples. Before reaching the plasma however, particles or droplets must be small enough in size. Gas samples can be directly introduced to the plasma. Solid samples need to be converted into micrometer-sized particles or vaporized. This can be done by, for example, laser ablation (LA) (see section 13.3). If LA is used the solid sample can thereafter be directly introduced to the plasma. Liquid sample are converted into an aerosol before reaching the plasma. A nebuliser is used in order to convert the sample into droplets. The nebuliser aspirates the sample with a flow of high velocity argon, which forms the aerosol. This fine mist must pass through a spray chamber placed directly after the nebuliser, allowing only droplets smaller than 10 µm to pass (Jarvis *et al.*, 1992).

2. Sample ionization

The plasma is generated inside a torch consisting of three quartz tubes in which the argon gas and the sample are transported. The plasma itself is highly ionized gas at elevated temperature. ICP-MS usually utilizes an argon plasma with temperatures between 6.000 and 10.000 K. Such is the case with the instrument used in this study but argon/nitrogen plasmas are also used. The plasma is ignited by an electric discharge and maintained by a fine copper tube, the coupling or load coil. This produces a radio frequency, which creates an electromagnetic field. It is in this electromagnetic field that electrons are accelerated and collide with Argon atoms, this forming the plasma. In the plasma the sample is vaporized, atomized and then ionized (Jarvis *et al.*, 1992).

3. ICP-MS interface

This is a most crucial part of the sample movement in the instrument. The plasma operates under atmospheric pressure, whereas the quadpole mass spectrometer is under vacuum. The interface consists of two small orifices, approximately 1 mm in diameter, which links the two pressure areas together. The ions first flow trough the sample cone, at high speed, into a mechanically pumped vacuum region and then trough the skimmer cone. The ion beam produced is focused into MS analyzer. These vacuum conditions are required so that ions are free to move without the possibility of colliding with air molecules (Jarvis *et al.*, 1992 and Rauch, 2001).

4. Mass Discrimination

After the interface, ions are focused into a beam by ion lenses and isotopes are separated based on their mass-to charge ratio (m/z). The most commonly used mass filter is the quadropole mass filter. It is made up of four metal rods aligned in parallel with opposite rods together. Direct current (DC) and ratio frequency (RF) potential are applied to each pair. The ions pass through the central axis of the four rods and depending on the voltage values only one particular m/z will be selected for. If an ion does not have the m/z selected for its trajectory will be such that it does not make it through the quadropole to the detector (Rao and Reddi, 2000).

5. Detection

In an ICP-MS system, the most common type of ion detector found is an electron multiplier. When an ion strikes the surface of the cone shaped detector it causes electrons to leave and strike the surface on, causing a cascade of electrons. These incoming electrons are converted to an electrical signal, which is interpreted by a computer (Jarvis *et al.*, 1992 and Rauch, 2001).

13.2.2 ICP-MS Interference

The possible interferences that can arise when analyzing metals with ICP-MS can be broadly categorized into two groups: non-spectral and spectral. Non-spectral interference are complicated and not fully understood. Suppression and enhancement effects can cause the interference as well as physical effects caused by high total dissolved solids. It is more severe for lighter mass elements. (Rao and Reddi, 2000). This type of interference can, however, be overcome by using internal standards that closely resembles the analyte.

Spectral interference occurs when several isotopes have the same or similar m/z. The mass filter gets thereby difficulties to separate their signals. Spectral interference can be further divided into three types; isobaric overlap, polyatomic ions and double charged ions. Isobaric overlap occurs when two different isotopes have essentially the same mass. Using isotopic pattern of the interfering elements and the signal of one of its isotopes can, however, sole this interference. Both polyatomic and double charged ions can be formed in the plasma and in the ion extraction. Chloride (Cl) and other solvent components used in the sample solution can combine with the carrier gas. Spectral overlap can then occur due to that the polyatomic ions produced have the same m/z as the element being determined. The plasma can under certain circumstances create double charged ions. This can occur when the second ionization energy of an element is lower that the first ionization energy of argon. The double charged ion then have half the m/z of a single charged ion leading to complications in the mass filtering of ions.

There are several methods for resolving these interference. Changes can be made to the mode of the sample introduction such as desolvation or LA to reduce oxide formation in the plasma. One of the most common approaches is to estimate the amount of interference and correct mathematically by estimating the contribution of interfering species to the signals through the analysis of standard solutions. Corrections can be calculated through equations 2.1-2.3 (Rauch, 2001).

$$I_{Pt} = I_{Pt,s} - (I_{Hf.s} \text{ x } R_{HfO,Hf}) \tag{2.1}$$

$$I_{Pd} = I_{Pd,s} - (I_{Cu,s} \text{ x } R_{ArCu,Cu} + I_{Y,s} \text{ x } R_{YO,Y} + I_{Sr,s} \text{ x } R_{SrO,Sr} + I_{Rb,s} \text{ x } R_{RbO,Rb}) \tag{2.2}$$

$$I_{Rh} = I_{Rh,s} - (I_{Cu,s} \text{ x } R_{ArCu,Cu} + I_{Pb,s} \text{ x } R_{Pb^{2+},Pb} + I_{Sr,s} \text{ x } R_{SrO,Sr} + I_{Rb,s} \text{ x } R_{RbO,Rb}) \tag{2.3}$$

13.3 LASER ABLATION

Laser ablation (LA) is a sample introduction system for ICP-MS that has been increasingly used to investigate solid samples. The technique allows the analysis of almost any solid sample (Borsov *et al.*, 2000). This is a rapid technique, with less interference and smaller contamination risk.

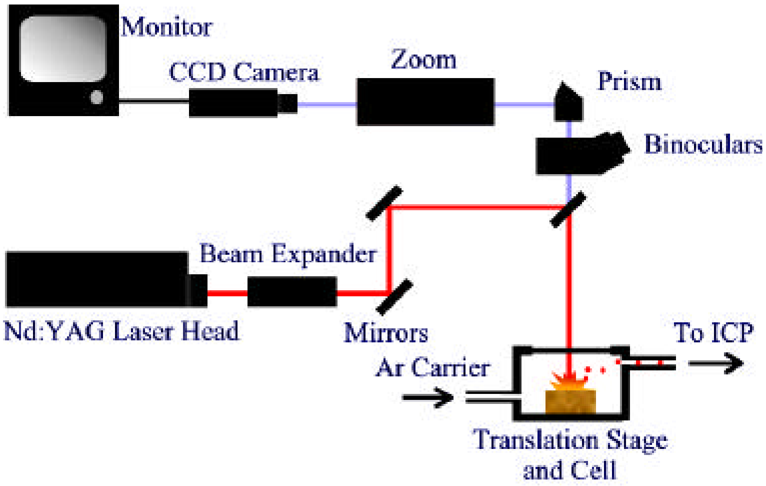

Figure 13. Laser ablation system for ICP-MS (Rauch, 2001).

13.3.1 LA Principles

Lasers concentrate a large amount of energy into light and when focused on a sample have the ability to vaporize the material if various parameters like the wavelength and absorption of the material are correct. LA-ICP-MS takes this ability to ablate materials and uses it to introduce the sample into the ICP-MS. Both infrared (IR) and ultraviolet (UV) lasers have been used, but UV lasers have been found more effective as there is less melting around the craters that are formed on the surface of ablated materials. This allows for the ablation of smaller, well-defined areas. The ablated material is swept by a carrier gas flow to the ICP-MS for analysis (Figure 13) (Rauch, 2001).

13.3.2 LA interference

Since dry samples are analyzed by this method the interference caused by polyatomic species is reduced. There are no water or acid species to interact with the Ar in the plasma. Also, its spatial resolution is high and can be controlled. Calibration of the LA is, however, challenging. This requires a very close matrix-matched calibration standard. Additionally this technique suffers from the fact that due to sample heterogeneity and small spatial resolution, results may be misleading.

14. DESCRIPTION OF THE STUDY AREA

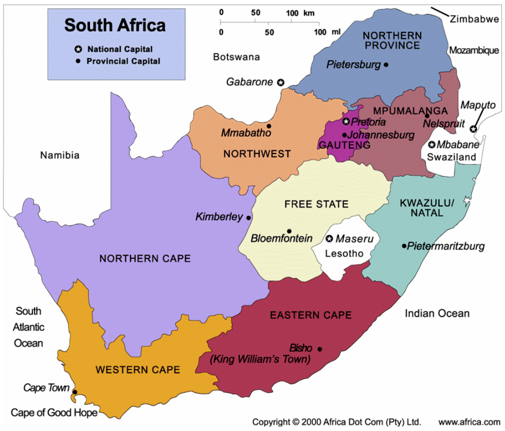

Figure 14 Map of South Africa and the Eastern Cape province (web ref 10).

The study area is located in the Eastern Cape, South Africa (see figure 14 and 15), which is the second poorest province of South Africa (Warner, 1999). The provincial capital is Bisho and other important cities include Port Elisabeth, East London, Grahamstown, King Williams Town, Cradock and Graaf-Reinet. Approximately 6.3 million people live in the Eastern Cape which comprises an area of 170 000 km^2 (South African Government, 2001). The Eastern Cape is a region where societal functions are poorly developed. Less than 20% of the households have access to the World Health Organization's minimum standard of drinking water and 87% of the population does not have access to adequate sanitation (Provincial Government, 2000). Unemployment rate is high, *e.g.* 45.3% in King Williams Town, and 40% of the household incomes are below the minimum subsistence level of ZAR 931.82 (~ 950 SEK) for a household of 5 members (SETPLAN, 1997). Table 23 gives an estimated total population of the study area.

Table 23. Population of the study area (SETPLAN, 2000).

Area/Suburb	Population estimate	Average density (persons/ha)
King William's Town	11 396	25
Ginsberg	6 645	70
Breidbach	5 373	82
Zwelitsha	27 304	97
Phakamisa	7 779	47
Dimbaza	24 262	79
Ilitha	7 024	79
TOTAL	89 783	62

The study area is characterized by fragmented urban settlements of different size and scale, surrounded by peri-urban or rural settlements situated within 10 km of the King William's Town boundary. These rural settlements are functionally part of the formal urban areas and characterize a form of residential development resulting from several historical and specific factors figure 15 (SETPLAN, 1997).

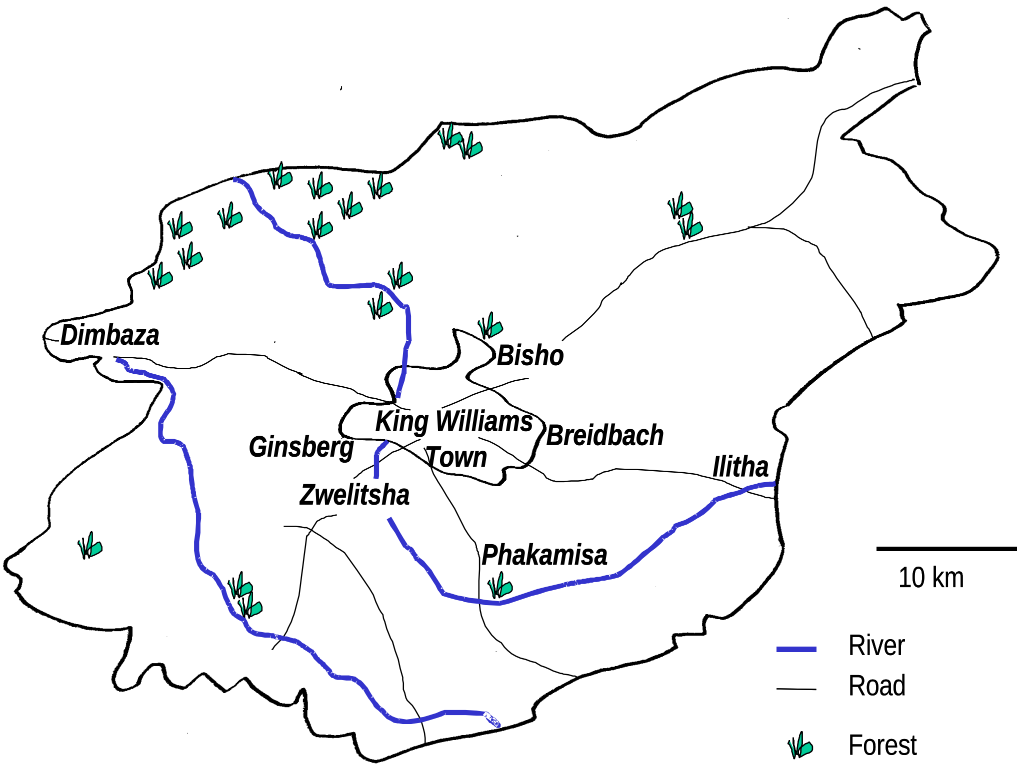

Figure 15. Sketch of the study area.

14.1 CLIMATE

The study area falls within the southeastern coastal region of South Africa. In less general terms (SETPLAN, 2000) it is described as, comprising dry sub-humid coastal plateau and semi-arid coastal plateau, minor valleys and sub-humid escarpment (see section 14.2).
Overall, the prevailing climate is described as temperate to warm and humid, with a definite summer rainy season, which is at a maximum in autumn (March), and at a minimum in June. On the average the summer months each have about 12 rainy days as against 4 in a midwinter month. In winter the sky is clear and the region receives about 70% of its possible sunshine; in summer it is often cloudy to overcast resulting in only about 50% of the possible sunshine duration (SETPLAN, 2000).

14.1.1 Rainfall

Rainfall varies widely over short distances. King William's Town area has a temperate steppe climate with most rain occurring between October and March (Trollope and Ward, 1989). As noted above, the study area falls within predominantly summer rainfall region, with a predominant Mean Annual Rainfall (MAR) of 500 – 700 mm, with smaller portions of the study area falling into higher annual rainfall regions ranging from MAR of 700 – 1200 mm. Generally, there are two peaks in summer rainfall season; one in November and one (higher) in March. Within the study area 69% of overall rainfall is summer precipitation (SETPLAN, 2000).

Of note for the derivation of agricultural potential and, more specifically, the practice of dry-land (i.e. rain-fed) agriculture in the area is the fact that the dependability of rainfall during the growing season (October – March) is critical (SETPLAN, 2000). Much of the study area also experiences a serious moisture deficit in January, which has important repercussions for rain fed crops (Trollope and Ward, 1989). Within the study area rainfall in the growing season has a lower variability/high dependability and >500 mm is obtained 78% of the time, thus the area has some rain-fed agricultural potential. Available data on rainfall (quantity and variability) suggest however that there is some potential for localized rain-fed agriculture (i.e. activity not supplemented by irrigation) (SETPLAN, 2000).

14.1.2 Evaporation

Across the study area, evaporation varies between 1350 and 1500 mm per year. The monthly evaporation pattern varies, with January and December yielding the highest figures, 150 and 200 mm respectively, and June the lowest 57 to 85 mm (SETPLAN, 2000).

Of note with regard to the dry-land agricultural potential in the study area is the fact that the comparison of potential evapo-transpiration rates versus average annual rainfall suggests that there is annual water deflect varying across the area from 150 to 400 mm. For effective cultivation to occur in the area generally, irrigation supplementation of rain- and groundwater is required of, on an average, between 100 mm and 370 mm during the growing season (see section 14.6).

14.1.3 Temperatures

The mean temperature ranges from 5 - 18 °C in July to 18 – 30 °C in January. Land and sea breezes are common, but strong westerly winds damage crops (Trollope and Ward, 1989). The following data is recorded (SETPLAN, 2000):

Mean monthly minimum and maximum temperature: 5 °C – 29 °C
Absolute minimum and maximum temperature: 2 °C – 45 °C
Mean duration of frost: 0 – 50
Relative humidity (%): 30 – 98

At King William’s Town the average duration of frost is only four days per annum. The average entry date of frost at King William’s Town is in mid-July (SETPLAN, 2000).

14.2 TOPOGRAPHY

In general terms, the study area is located in the intermediate plateau lying between the narrow coastal plain and the Amatola Mountains. The plateau is typically dissected by deeply incised river valleys, giving rise to a landform characterized by deep valleys and flat-topped areas between such valleys (SETPLAN, 1997).

Within the King William’s Town area, the topography is dominated in the west by the Buffalo River, its floodplain and confluence with the Mgqakwebr, Balasi, and Tshoxa Rivers, and the surrounding elevated hillsides/plateau’s where Zwelitcha and southern Phakamisa are located (figure 15). The eastern portion is dominated by the Yellowwoods River, which is characterized by a limited river terrace and steeply (cliffed) incised valleys (SETPLAN, 2000).

14.3 VEGETATION

Due to the dissected terrain and the (local) ranges in altitude, the natural vegetation of King Williams Town and its surroundings environs represents a wide variation in form and complexity of distribution pattern. This geographical variation of vegetation type is further influenced by the natural plant succession and the extent to which such succession has, and is being, interrupted or held in check by both natural and human impacts (fire, overgrazing, cultivation, settlement development) (SETPLAN, 1997). The vegetation of the study area can be classified into three types described in table 24.

Table 24. Vegetation types of the study area (Setplan, 2000).

Veld types	Major plant formations
Coastal forest types	Savanna, Grassland, Forest
Karoo and Karroid Types	Savanna, Nama Karoo
Temperate and transitional forest and scrub types	Grassland, Macchia, Forest

14.4 LAND USE PATTERNS

The urban structure of the study area is a result of past political ideologies and reflects the image of an ‘Apartheid City’. This urban structure has direct impact on the variety and spatial manifestation of land uses and is characterized by the development of an urban core area (King William’s Town, Bisho, Ginsberg) surrounded by spatially separated, largely mono-functional areas (*i.e.* areas where a single land use type, usually residential, predominates) (Phakmisa, Zwelitsha and Breidbach) and outlying areas (Ilitha, Dimbaza) (figure 15) (SETPLAN 1997).

14.4.1 Rural land use patterns

All rural land, which is not held in private ownership (i.e. land that is likely to be commercial farmed) is presently regarded as state land and the predominant land use pattern in these areas is of the “traditional” rural settlement form; that is, villages, areas set aside for sub-subsistence cultivation and free-range grazing land (SETPLAN, 2001).

14.4.2 Urban land use patterns

King William’s Town/Bisho forms the urban core with Phakamisa, Zwelitsha and Breidbach as largely mono-functional residential areas on the fringe of the core, and Ilitha and Dimbaza representing outlying (or satellite) areas (SETPLAN, 1997).

14.4.3 Residential land use

The residential land use can be categorized into three residential zones within the study area (SETPLAN, 2000) (figure 15):

- Core residential zones (King William’s Town, Ginsburg; Bisho)
- Fringe residential zones (Breidbach, Phakamisa, Zwelithsha)
- Outlying residential zones (Ilitha, Dimbaza)

The core residential zone falls within areas that have a mix of different land, activities and densities and are with close proximity of services and work. These areas also offer the highest order of choice, convenience and land use complexity compared to other residential zones (SETPLAN, 2000).

The fringe residential zones are generally mono-functional in character, with limited commercial and industrial activities localized in small areas (SETPLAN, 1997).
The outlying residential zones are spatially removed from the core and fringe areas and are, to a greater extent, affected by limitations and shortcomings evident in the fringe. It is notable however, that Dimbaza has a relatively better mix of land uses and a substantial industrial land use component when compared to either Ilitha or areas within the fringe zone (SETPLAN, 2000).

14.5 INDUSTRY

Four industrial zones localities can be identified in the study area, namely (SETPLAN, 2000):

- King William’s Town
- Dimbaza
- Zwelitsha
- Bisho

The industrial zones in King William’s Town and Bisho consist of smaller industries associated with light industrial activities while the industrial areas of Zwelitsha and Dimbaza are products of the former Government’s policy. These industrial zones were designed to attract heavy industry associated with labour intensive operations (SETPLAN, 2000) and the former government subsidized these industries. When this came to an end, in the early 1990’s in combination with the abolition of trade barriers, many factories were forced to close down (Hifab International/SSPA Sweden, 2000).

At present, a substantial cluster of garment industries is employing an estimated 4000-6000 people is located in Dimbaza. Dimbaza also has a foundry. The former large employer, King Tannery, located in King Williams Town has recently closed down. Another large industry in King Williams Town is the TI Group making specialized engineering products (Hifab International/SSPA Sweden, 2000).

The study area is underlain by horizontally bedded mudstones/sandstones. Portions of the horizons have been locally indurated to form quartzitic sandstones, which are of suitable grade for the production of aggregate and road stone (SETPLAN, 1997). At present mining is taking place in the region, but not within the study area.

14.6 AGRICULTURE

The rural areas within the Eastern Cape region are of varying agricultural quality, reflecting its variety of agro-ecological zones. Rainfall, evapo-transpiration, soils and slopes are the determining factors governing the land capability, affecting the suitability of different areas for crop and/or animal husbandry and forestry, as well as influencing the choice of crops, animals and tree species (Hifab International/SSPA Sweden, 2000).

A substantial part of the region has good agricultural potential where small-scale farmers hold most of the land under various forms of communal tenure. They practice mixed agriculture often for subsistence purposes. Parts of the province are in the hands of large-scale marketoriented farmers (Mandirigana *et al*, 2000). Mainly maize, beans, pies, potatoes and vegetables are being cultivated within the study area (Yankee, *pers. Comm.*).

In the study area, the late rainfall and the frost period of 1 to 30 days per year restrict the cropping potential (Trollope and Ward, 1989). Supplementation by irrigation is necessary for effective cultivation to occur (see section 14.7) King Williams Town provides a market for many basic food crops that could be produced locally, even by small-scale farmers. Many factors conspire against these producers (Hifab International/SSPA Sweden, 2000). A variety of constraints, such as the following, have been identified for small scale farmers of the study area (Hifab International/SSPA Sweden, 2000):

- Shortage of arable land.
- Shortage of grazing land.
- Overstocking and land degradation.
- Decline in carrying capacities.
- Lack of capital for both agricultural inputs and services.
- Insufficient access to markets for products and input suppliers.
- Problems of reliability in supply and quality of produce.

Overgrazing, particularly in the communally used rangelands, have lead to increased soil erosion. Water borne soil particles have increased suspended matter in the waters and increased sedimentation in dams, thereby the holding capacity is slowly but steadily decreasing. Water erosion in rangelands and from the heaped manure has contributed to increased faecal pollution, and certainly to higher BOD (Zinn, 2000). Wind erosion is unrestricted in the overgrazed and flat areas (Hifab International/SSPA Sweden, 2000). Despite these issues, agriculture remains the main activity of most people in the rural settlement areas and, by increasing productivity and opportunities in the study area, it is likely to be able to support more people (SETPLAN, 2000). At present the agricultural sector within the extended study area contributes an insignificant 2.46% to the local economy and employs 4.9% of those in formal employment. The sector’s potential contribution to the economy and in providing employment is probably ten times the existing situation (Hifab International/SSPA Sweden, 2000).

At present thousands of households are practicing backyard gardening. There are attempts to start community gardens even though none is operating. There are informal livestock kraals in operation. Land for community gardening is available and under ownership of the municipality. Skills in growing vegetables and rearing small stock (chicken, sheep) are common. Residents in most townships have actively expressed interest and ambitions to get more involved in agricultural activities (Hifab International/SSPA Sweden, 2000).

14.6.1 Soil Characteristics

Phosphorous, nitrogen and micronutrients are known to be major factors limiting productivity in the sub-region. A survey made by the department of Agronomy at University of Fort Hare, 2000, on the region shows that the fertility status of cultivated soils in the Eastern Cape is generally low, especially in the fields of small-scale farms (Mnkeni, *pers.comm.*). For resource-poor farmers, one way to correct this problem is to apply locally available kraal manure at high rates. Supplementing kraal manure with inorganic sources of nutrients may still be desirable, but there are questions around their affordability. The fertility status of soils receiving moderate to high amounts of nutrients was generally satisfactory as evident from the nutrient content of soils in home-gardens and the cultivated fields on large-scale farms (Mandirigana *et al*, 2000).

14.6.2 Soil Fertilizing

Soil fertilizers commonly used locally today are as mentioned before kraal manure and chemical fertilizers or a mixture of both. The compositions of chemical fertilizers that are widely used in the region are shown in table 25. Also, fertilizers with 3.8% nitrogen, 12.2% phosphorus and 1% zinc are available on the market (Mnkeni, *pers.comm.*).

Table 25 Composition of commonly used chemical fertilisers with in the study area (Mnkeni, 2001).

N : P : K	Zn
2 : 3 : 2	0.5%
3 : 2 : 1	0.5%
2 : 3 : 4	0.5%

14.7 WATER AND IRRIGATION

Irrigation is necessary for effective cultivation in the study area. The Buffalo River provides the region with water and transports waste effluent in the most populated areas of the Eastern Cape (figure 15). The river rises in the Amatola Mountains and flows southeast to the sea at East London passing King Williams Town and agricultural areas. A relatively minor area of 31 ha of land is being irrigated (Zinn, 2000) and salinization is a problem in large-scale farming, where irrigation is practiced, due to elevation of the water table and saline water quality (Mnkeni, *pers.comm.*). Irrigation is most common among commercial farmers and different irrigation schemes (Yankee, *pers. comm.*). There has been concern about the water quality in the Buffalo River for many years, especially regarding salinification and eutrophication (Zinn, 2000). Data on groundwater resources however indicate that there is a possibility of supplementing local water supply schemes as well as local irrigation schemes by utilizing this resource on a managed basis (SETPLAN, 2000).

14.8 SANITATION AND WASTEWATER TRANSPORT SYSTEMS

After the apartheid era of South Africa the new government have implemented an extended low-cost housing project, providing housing in sub-urban and rural areas. The Eastern Cape province is no exception and within the study area a number of two room houses settlements have been established (figure 16). E.g Dimbaza is almost a total low cost –housing area. Some

Figure 26 Low-cost housing project.

houses are connected to the sewer system, which is a separated system with plastic piping, while others are provided with a septic tank. The municipality arranges for a truck to pick up the waste from these septic tanks (Dimbaza superintendent, *pers. comm.*).

Figure 17. Low-cost housing project.

Separate systems with one pipe for the domestic and industrial sewage and another for the surface runoff (storm water) is the standard sewage system being used in South Africa.
At present, however, all wastewater; storm water, domestic and industrial wastewater, is being mixed at the inlets of each treatment plant as there are no facilities for treating the different wastewaters separately (Van. Heerden, *pers. comm.*). The presently individual sewage treatment plants serving the region around King William's Town are the following;

- Dimbaza Treatment Works (see section 15.3)
- Shornville Treatment Works (see section 15.1)
- Bisho Treatment Works
- Zwelitsha Treatment Works (see section 15.2) and,
- Breaidbach Treatment Works

These all principally handle domestic sewage as the King Tanning Company and Da Gama Textiles Works supposedly handles their industrial effluents (SETPLAN, 1997). Most of the above treatment plants have already or are approaching their design capacity limit, while some are completely non-functional. This is resulting in untreated or partially treated sewage being discharged into the Yellowwoods and Buffalo Rivers, that feed into the Laing Dam which is the main drinking water supply for King Williams Town, Bisho and Zwelitsha (Hifab International/SSPA Sweden, 2000).

King Williams Town area falls within a phosphate sensitive catchment area in the presence of phosphate in the partially treated sewage is resulting in eutrophication of the rivers, further reducing raw water quality. This situation will only worsen as the population in the area increases (Hifab International/SSPA Sweden, 2000).

14.9 WASTE MANAGEMENT

The King Williams Town solid waste disposal site is fairly well controlled apart from insufficient cover material to cover waste on a daily basis. A new leachate dam has just been completed to catch any pollutants leaving the site (Hifab International/SSPA Sweden, 2000).
In heavily industrialized areas like Dimbaza and King Williams Town, the dumping of toxic waste in open spaces has resulted in the pollution of arable land, which has been rendered unusable. An example of this is Bidley farm, where some 158 ha of land was used for the disposal of the tannery waste in the 1950's. Primary polluting components include organics, chrome, sodium (high toxicity). Chrome content of soil renders it not suitable for housing. The road between Bidley Farm and the new development of that area is polluted in this manner. In the area from the Buffalo River Bridge in Shornville to Ginsberg, faecal and parasitic loads have been identified in the soil. Da Gama irrigation area has a high content of sodium, iron and manganese, which affects the absorptive capacity of soil. The Phakmisa waste disposal site has content of chrome, primarily wet-blue trimmings, which rendered the land unsuitable for housing (Hifab International/SSPA Sweden, 2000).

14.10 CURRENT SLUDGE USE

At present there is no municipal arrangement for any use of sewage sludge in the study area. The management of the plant handles the final sludge. The plants that uses either grow grass on top of the lagoons when they are full and then create a new lagoon or, if there is no space for a new lagoon, empty the full lagoon and take the sludge to the waste deposit site in the area. The plants that uses drying beds offer anyone to collect sludge for their own use, the rest is taken to the final deposit. Local low scale farmers that live near the plants collect sludge with wheelbarrows and put on their vegetable gardens where cabbage, carrots, red beat, corn and other crop is grown. However, the major use of this sludge is attributed to one particular farmer that collects big quantities of sludge. The sludge is used as soil conditioner to increase humus and nutrient content of the land (Lustgarter, *pers. comm.*). Other use of sewage sludge in the Eastern Cape region is brick production (Fatoki, *pers. comm.*).

15. TREATMENT PLANTS

Three treatment plants have been included in this case study, namely;

- Dimbaza Sewage Treatment Works,
- Shornville Sewage Treatment Works, and
- Zwelitsha Sewage Treatment Works.

Figure 18 shows a map of the study area and the location of the plants. The following sections in this chapter will describe the three plants individually explaining their history, structure and current condition as well as activities taking place in the near surrounding. It is worth mentioning that much of the gathered information is from personal communication with people working at a plant and/or living nearby and that only parts of it originate in written documentation.

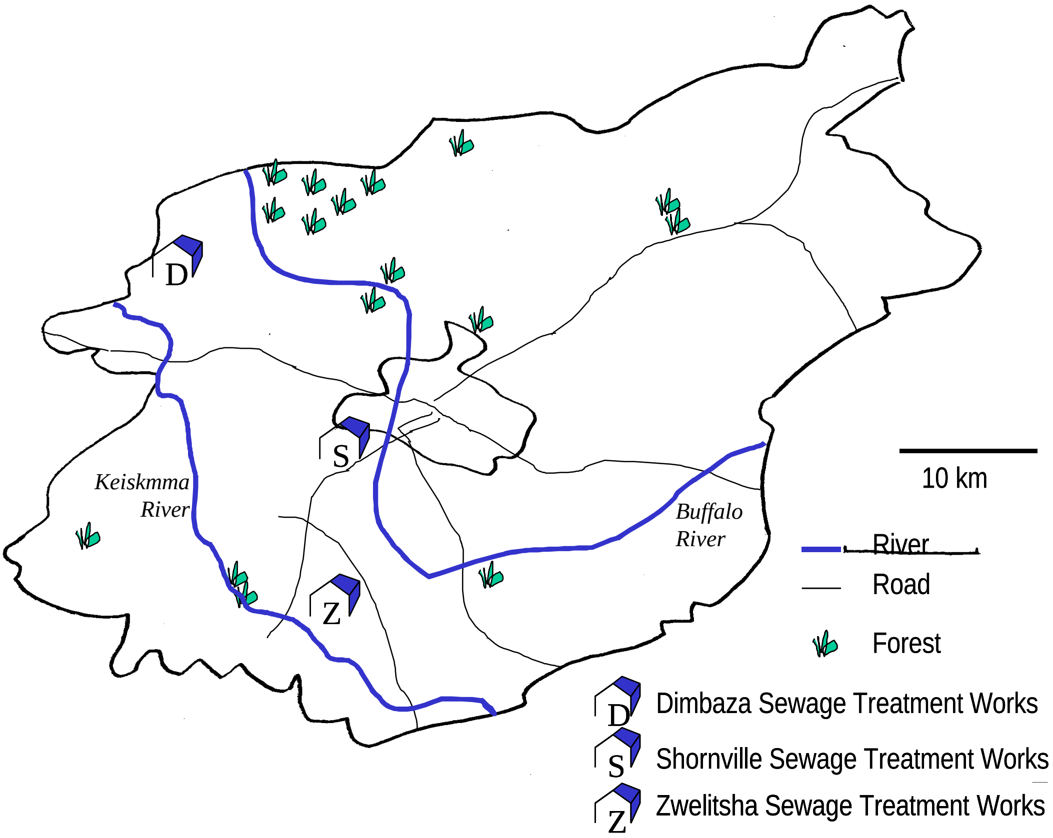

Figure 18 Sketch of the treatment plant locations in the study area.

15.1 SHORNVILLE SEWAGE TREATMENT WORKS

The sewage treatment works in King Williams Town, the so-called Shornville Sewage Treatment Works, was originally built to cater for the domestic sewage from King Williams Town. Buffalo City Municipality owns the works but it is currently run and maintained by a private contractor. The works is now working at least three years beyond its designed life due to the accelerated growth of King Williams Town and is at a state of overload. The sewage is predominately domestic in origin although the works also handles about 550 m^3/day of industrial effluent (HKS, 1994).

In 1987, extensions to the Shornville works were commissioned to handle all the sewage from both King Williams Town and Ginsburg. The extensions comprised a new treatment plant with a nutrient removal activated sludge reactor, clarifiers and additional sludge drying beds. The aeration basin reactor cannot be used for either denitrification or phosphate removal at present so that the works extensions are operated as a conventional extended aeration activated sludge plant. As the activated sludge plant and biofilter works cannot produce an effluent to meet the Special Phosphate Standards (of 1 mg/l of ortophosphate), chemical phosphate removal facilities have been provided to ensure that the final effluent does comply (HKS, 1994).

The capacity of the plant including the original works and extensions is 4800 m^3/day (HKS, 1994). At present, the works are operated with 60 percent of the sewage flow being treated in the new activated sludge plant and the other 40 percent in the old biofilter plant (figure 19). Total Solids and Volatile Solids have been measured on the primary and secondary sludge from the digesters since 1999, to give an idea of how the processes are going (Dolley, *pers. comm.*).

Figure 19 Biological filter unit at Shornville Sewage Treatment Works.

15.1.1 The Works

Figure 20 shows a schematic diagram over the works. At the inlet of the works there is a primary screen and a set of secondary screens (mechanical filters). The screening material is manually emptied, bagged and sent off to a solid waste site regularly (see section 14.9). The flow enters a chamber where lime dosing takes place in order to adjust the pH level to prevent the corrosive effect of the effluent when going through the works. At this point the flow is split in two. Up to 86 m^3 per hour then goes to what is referred to as ‘the old works’ of a biological filter system, while the rest is taken through ‘the new works’ with an activated sludge basin (Kockett, *pers. comm.*).

The inflow to the new plant from the lime feeder enters six chambers that make the anaerobic portion of the activated sludge basin. Here the acid level is built up to make the effluent more conducive to the breakdown of phosphate that follows in the aerobic portion. At the outlet of the activated sludge basin is a ferric chloride feeder, which is used to flocculate the solids. From there the flow then goes to two settling tanks. The effluents from these tanks come out to two outlet chambers and are joined up for chlorine dosing before being pumped up to a final semi oxidation pond, and from there being discharged to the Buffalo River. The sludge that sediment in the settling tanks is withdrawn continuously and either recycled back to the activated sludge basin or put on drying beds.

From the lime feeding unit, 86 liters per hour goes to the old works. The flow enters two settling tanks from which the effluent is pumped up to an elevated reservoir, which feeds the biological filters (stone and sand). The outflow from the filters enters a humus tank, which functions as a final settling tank that also connects to a balancing dam in the case of overflow and need for equalization. Finally the effluent passes through a sand filter for polishing. All of the effluent is then chlorinated to kill off pathogens before it is pumped up to a holding dam up by a golf course and used for irrigation purposes.

The settling tanks of the old works have an automatic de-sludge system and is pumped to the three digesters; two primary digesters that do the initial organic break down and a final digester. The digester phase takes up to four days and temperatures reach about 80°C. The methane produced is discharged in the air and the sludge is put on drying beds.

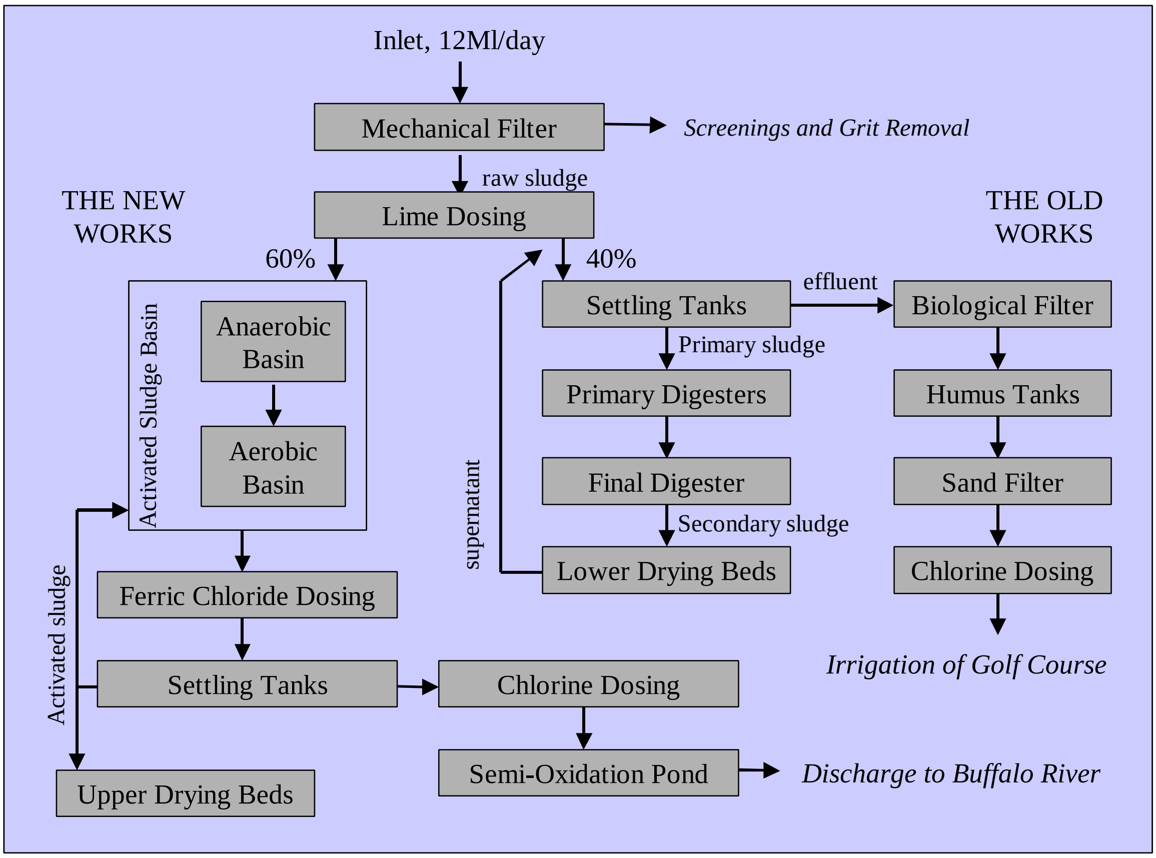

Figure 20. Schematic diagram over the treatment steps at Shornville Treatment Works.

The sludge on the drying beds is left for several months before shuffled to a pile available for local farmers to collect. By the time the sludge is removed from the beds it is odorless and soil-like to its character. Several low-scale farmers in the area nearby come and collect the sludge and at the actual treatment works, maize and other crops are being grown.

There are changes about to take place at Shornville Treatment Works. By the time this paper is published, the old works, at its end of the sand filter or prior to the sand filters, will be connected to the new plant. By doing this the effluent from the old plant will get a final polishing through the activated sludge basin, as the biological filter system does not remove phosphate to any great extent.

Other changes that may take place at Shornville Sewage Treatment Works in the foreseeable future is to use the methane produced in the digesters to drive an incinerator for the screening material from the mechanical filters (Kockett, *pers. comm.*).

15.2 ZWELITSHA SEWAGE TREATMENT WORKS

Zwelitsha Sewage Treatment Works is own by the Department of Water Affairs (DWAF), but is mainly run by the contractor Batman Waters since 1993 (HKS, 1994). The works is preventative maintained twice per month and looked after daily by the local operator and two maintenance fitters. There is no continuous monitoring taking place on the sludge but monitoring of the wastewater is however done on a weekly basis. DWAF has set up certain standards regarding the quality of the wastewater and the raw and final wastewater is monitored (Van. Heerden, *pers. comm.*). The plant was extended around 1984, when new settling tanks and a digester etc. was build (Zwelitsha superintendent, *pers. comm*).

Households from Zwelitsha, Phakamisa, Ilitha as well as industries around Zwelitsha are connected to the plant (Dep. of Engineering). Thus, the works treats predominately domestic sewage including the daily disposal of some bucket latrine waste but there is also industrial effluent from the abattoir in Zwelitsha (HKS, 1994). The factories are mainly textile and leather industries. A transport co-operation with its own septic tank is located close to the treatment plant. Drainage water from the septic tank reaches Zwelitsha Sewage Treatment Works (Zwelitsha superintendent, *pers. comm.).*

15.2.1 The Works

The works has a maximum capacity of 13Ml/day and a normal inflow of 7 Ml/day (Van Heerden, *pers. comm.*). The plant is not expected to exceed the design flow within the planning horizon of 2015 (HKS, 1994).

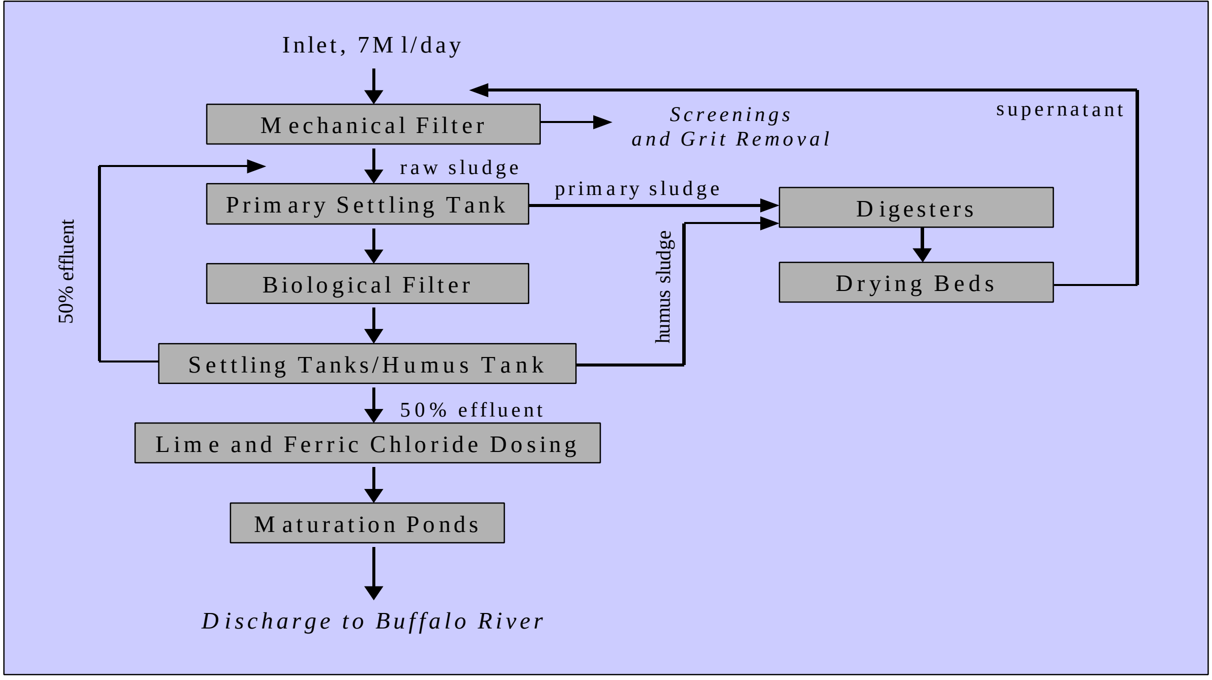

Figure 21. Schematic diagram over the treatment steps at Zwelitsha Treatment Plant.

Figure 21 shows a schematic diagram over the treatment processes at Zwelitstha Treatment Plant. At the inlet there is a mechanical filter where larger particles are removed to final deposit. The water then reaches two settling channels where the water flow is low and heavier particles are let to sink to the bottom of the channels. The settling channels are continuously cleaned and the soil at the bottom is removed to final deposit (Zwelitsha superintendent, *pers. comm*). The final deposit is located on the treatment plant area where waste is buried in the ground. The final deposit consists of trenches. When the trenches are full soil is spread over the surface and they are let to be overgrown by grass and other plants (Van Heerden, *pers. comm.*).

Figure 22 Drying beds at Zwelitsha Sewage Treatment Works.

The effluent continues to six different primary settling tanks, two new and four old tanks. Thereafter the water reaches two different biological filters. The effluent from the biological filter overflow into four different secondary settling tanks (Zwelitsha superintendent, *pers. comm*). The retention time in the settling tanks is approximately 9 hours (Van Heerden, *pers. comm.*). About 50 percent of the wastewater is then recycled to the water plant inlet, while the remaining 50 percent are left for chemical treatment (Zwelitsha superintendent, *pers. comm*). The chemical treatment of the effluent consists of addition of lime and ferric chloride. The treated effluent passes through a set of maturation ponds prior to discharge in the Buffalo River (HKS, 1994). The amount of chemicals added depends on the incoming strength and can be adjusted both manually and automatically. The raw sludge from the primary settling tanks are mixed with the humus sludge from the secondary settling tanks and treated in two different digesters. The sludge is left in the digesters at approximately 17 °C for about 45 days (Van Heerden, *pers. comm.*). The digested sludge is then put on the drying beds (figure 22) (Zwelitsha superintendent, *pers. comm*). The sludge physical appearance can be characterized as relatively wet and thigh flocks of sludge. About 50 m^3 of sewage sludge is produced daily (Van Heerden, *pers. comm.*). The drying beds are made of a concrete bottom with a thin layer of sand on. The supernatant water from the drying beds is recycled into the treatment plant inlet (Zwelitsha superintendent, *pers. comm*).

Figure 23. Private vegetable garden with Zwelitsha sludge as fertilizer.

In the future Zwelitsha Treatment plant is planned to be transferred to the Local (Metro) Council. Today there is no finance possibility for expansion of the plant, but the drying beds are planed to be upgraded in the future (Van Heerden, *pers. comm.*). Workers at the treatment plant, as well as locals living nearby, uses the sludge regularly as soil-improvers for their gardens to grow vegetables such as cabbage, carrots, spinage and maize (figure 23). It is known that a private company collects large quantities of the dried sludge with trucks to produce soil, which is then sold (Dimbaza superintendent, *pers. comm*).

15.3 DIMBAZA SEWAGE TREATMENT WORKS

Dimbaza Sewage Treatment Works is also owned by the Department of Water Affairs (DWAF), but run by the contractor Batman Waters. The everyday management is made by the local operator and two maintenance fitters. There is no continuous sludge monitoring taking place. Wastewater monitoring is however done on a weekly basis. DWAF has set up certain standards regarding the quality of the wastewater and the raw and final wastewater is monitored (Van. Heerden, 2001). The Dimbaza treatment plant was built in 1983 (Dimbaza superintendent, *pers. comm*). About 95% of the total wastewater reaching the treatment plant origin from households and approximately 5000 households are connected to the plant (Dimbaza superintendent, *pers. comm.*). Apart from households, industries are connected to the plant. The number of industries is uncertain but both textile and metallurgical industries are present. It is diffuse to what extent these industries treat their wastewater. One large industry claiming to treat their wastewater before discharge is the denim-factory called China Garments, but it is likely that the effluent water still contains chemicals and sludge of various condition (Hifab, 2000). It is believed that the denim-factory is the cause of the bluish color that occasionally occurs of the incoming water to the treatment plant.

15.3.1 The Works

Dimbaza Treatment Works has a maximum capacity of 9 Ml/day, while the normal inflow is about 7 Ml/day (Van Heerden, *pers. comm.*).

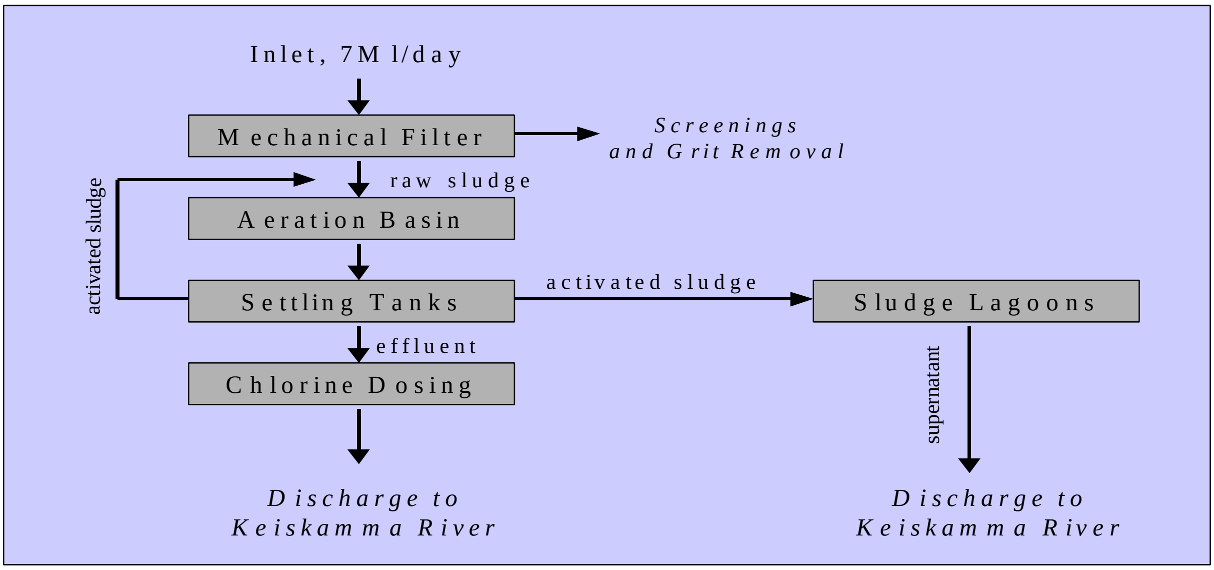

Figure 24. Schematic diagram over the treatment steps at Dimbaza Treatment Works.

Figure 24 shows a schematic diagram over the treatment processes at Dimbaza Treatment Works. At the inlet (figure 25) a mechanical filter is located where lager particles are removed and put in final deposits (Dimbaza superintendent, *pers. comm*). The final deposit consists of trenches. When the trenches are full soil is spread over the surface and they are soon overgrown by grasses and other plants (Van Heerden, *pers. comm.*).From here the water reaches to the aeration

Figure 25 Treatment plant inlet.

basins, where activated sludge is present. The wastewater flows thereafter into two settling tanks (Dimbaza superintendent, *pers. comm*). The retention time in the settling tanks and the aeration basin is approximately 9 hours (Van Heerden, *pers. comm.*).The activated sludge are recycled from the settling tanks and mixed with raw sludge before reaching the aeration basins.

The effluent from the settling tanks overflow into the chlorine conduct tank, where the wastewater is chlorinated before it is discharged. Chlorine mixed with water (choleric acid) is added to kill of pathogens (bacteria) (Dimbaza superintendent, *pers. comm*). The amount chemicals added depends on the incoming strength and can be adjusted both manually and automatically (Van Heerden, *pers. comm.*).The effluent from the Dimbaza treatment plant is discharged into a small stream connected to Keiskamma River. Sewage sludge are taken from the settling tanks into sludge lagoons with about 2m depth. When the sludge reaches the sludge lagoon its in liquid form, like thick water. The sludge settles on the bottom of the ponds and the resisting water is later discharged from the ponds (Dimbaza superintendent, *pers. comm*). About 50 m^3 of sewage sludge is produced daily.

Figure 26 Sludge lagoon at Dimbaza Sewage Treatment Works.

There is no use of sludge drying beds. The sludge lagoons (figure 26) are only a way of handling the sludge and are constructed like a normal pond, e.g. the bottom is not made of concrete or any other impermeable material. The sludge lagoons do not allow the sludge to dry out completely, therefore the physical sludge characteristics can be described as very wet in the bottom and center of the lagoon, but quite dry and fine at the surface. There are no plans of major changes at the treatment plant in the near future. About 75-90% households in the surrounding have vegetable gardens (Dimbaza superintendent, *pers. comm*) but none of them currently uses the produced sewage sludge as fertilizer.

16. SAMPLING AND ANALYSIS

16.1 SAMPLING AND SAMPLING PREPARATION

During a six-week period sludge samples were collected on a weekly basis. The samples where taken from the final sludge disposal at each treatment plant *e.g.* drying beds/lagoons, as this is the sludge that is, or may be, collected and used (table 26).

Table 26 Sample station details.

Treatment Plant	*Sample Station (Code)*	*Comment*
Dimbaza Treatment Works	Dimbaza (D)	Sludge Lagoon
Shornville Treatment Works	Shornville Upper (SU)	Drying Beds
Shornville Treatment Works	Shornville Lower (SL)	Drying Beds
Zwelitsha Treatment Works	Zwelitcha (Z)	Drying Beds

Samples where soil-like, semi-dry when collected in plastic bags (figure 27). Due to heavy odor samples where let to air-dry outdoors before put in glass beakers that had been washed with detergent and rinsed with water. A Precisa balance model 3100C was used to weigh the samples before and after drying in a Gallenkamp Oven Model OV-440 at 35°C. Depending on the wetness of the samples they where left in the oven for a period of 10 up to 110 hours (Appendix 1). After drying and weighing samples where manually grinded with a ceramic mortal in order to reduce its volume before being sent from the study area to CTH. The samples where sent in plastic containers washed with detergent and rinsed with water.

Figure 27 Sludge sampling from drying beds.

At CTH samples were dried again (10 hrs, Fermaks Owen) to make sure that the samples represented total solids (100% TS) and thereafter grinded to powder with a Krups KM75 coffee grinder. Standards for the ICP-MS analysis (see section 13.2) were prepared with the 4 samples collected at sample occasion 3 (table 27). These samples were divided into 3 smaller sludge samples creating 12 samples. To each of the 12 sludge samples 8ml of HNO_3 (nitricacid) was added to 3-5g of sludge powder and the mixture was then run in a microwave digestion unit (CEM Mars5^{TM}) (see section 13.1). After the samples were digested, 1ml of 65% HNO_3 was added to 50µl of the digested solution. Finally each solution was put in a 25 ml bottle and filled with nanopure water in order to reach the concentration range for possible ICP-MS-analysis.

The other 6 sets of sludge samples, e.g. 24 sludge samples, did not require and preparation. They were directly put in a steel holder under pressure and then analyzed in with LA-ICP-MS (see section 13.3). This was the case also for three sludge samples provided for treatment plants in Sweden, namely Ryaverket (Göteborg), Brommaverket (Stockholm) and Kappalaverket (Lidingö).

Standards for LA-ICP-MS were prepared by diluting a commercial heavy metal standard with different amounts of nanopure water in order to obtain solutions with concentrations of 1 ppb, 5 ppb, 10 ppb, 50 ppb and 100 ppb, e.g. 50 ml of nanopure water was added in order to obtain a solution of 1 ppm. A blank standard was also prepared with nanopure water. Prepared standard solutions were used in order to calibrate the ICP-MS and LA-ICP-MS (see section 13.3).

16.2 SAMPLING ANALYSIS

The standard solutions were analyzed in the ICP-MS order to determined levels of heavy metal in the sludge, while LA-ICP-MS was used for fingerprinting. Concentration analysis was thus performed on one set of samples only (sampling occasion 3, table 27). Fingerprints were obtained for all samples collected in the study area (Table 27) as well as the three available sludge samples collected in Sweden. For all concentration- and intensities-values obtained, mean values has been used for further analysis.

Table 27 Sample collection details.

Sampling Day	*Sample Occasion*	*Analysis with ICP-MS*	*Analysis with LA-ICP-MS*
October 31	1	NO	YES
November 6	2	NO	YES
November 12	3	YES	YES
November 19	4	NO	YES
November 26	5	NO	YES
December 3	6	NO	YES
December 6	7	NO	YES

16.2.1 Microwave Digestion Analysis of sludge

The microwave digestion system (CEM Mars^{TM}) increased temperature and pressure in the stepwise manner given in table 28.

Table 28. Time, temperature and pressure settings used in microwave digestion of samples.

Stage	Power (W)	Attempting temperature (°C)	Maximum pressure (psi)	Ramp (min)	Holding (min)
1	600	110	50	5	2
2	600	140	100	5	2
3	1200	170	200	5	2
4	1200	200	300	5	6

16.2.2 ICP-MS Analysis of sludge

The instrument used in this study is a Perkin Elmer Sciex Elan 6000 (Figure 28). The instrument uses a quadpole mass filter, and is equipped with an autosampler followed by a cross-flow nebuliser and a Fazel-Scott spray chamber for sample introduction The autosampler extracted solution at a rate of 1 ml/min. Solid samples can also be introduced into the plasma through a laser ablation system. The instrument is placed in a clean room and an autosampler allows complete control by

Figure 28. The Elan 6000 at Chalmers University of Technology (Rauch, 2001)

computer from outside the instrument room. Table 29 shows the settings that were used for the analysis. The elements analyzed are Cr, Cd, Zn, Pb, Cu and Ni. Mercury was, however, not analysed since it is hard to obtain accurate results of its concentration with this analysis method.

Table 29. ICP-MS settings used in sample analysis.

Elements	Cr, Cd, Zn, Pb, Cu, Ni
Sample introduction	Sewage sludge samples: Ar at a flow rate of 0.86 l min^{-1}
Carrier gas	
ICP	
Plasma gas	Ar at a flow rate of 16 l min^{-1}
Auxiliary gas	Ar at a flow rate of 0.9 l min^{-1}
Rf power	1000 W
Acquisition	
Data acquisition	Peak hopping
Dwell time	100 ms
Replicates	5
Sweeps per reading	10
Reading per replicate	1
Peak width	6

16.2.3 LA-ICP-MS Analysis of sludge

The instrument used in this study is a CETAC LSX 200 LA system, which was coupled to the ICP-MS. It is equipped with a Nd:YAG laser. The laser beam is focused through two mirrors giving a wavelength of 266 nm hitting the sample. The sample cell can be viewed from a video screen and can be moved mechanically with fine precision, giving the opportunity of choice of sample spots. The settings in table 30 were used for sludge analysis.

Table 30. Settings for LA-ICP-MS analysis.

Parameter	**Setting**
Wavelength	UV 226 nm
Operation mode	Q-switch
Carrier gas	Argon
Spot size	50 µm
Energy	3 (0.4 mJ)
Repetition rate	20 Hz
Scan speed	25 µms^{-1}

As a result of the LA-ICP-MS analysis data on the actual intensity for each element are obtained. 37 different metals were measured on each sample. Mean values for the different metal intensities obtained from each sample were calculated and put in graphs, referred to as fingerprints. The intensities indicate the actual concentrations of the metals analyzed.

17. UNCERTAINTIES

Accuracy of analysis result is naturally affected of a number of possible uncertainties. The uncertainties recognized for this study are mainly attributed to contamination of sampling equipment and spill during sample handling as well as sampling analysis. The uncertainties can be listed as the following during the work done in South Africa:

Spill when;	weighing samples
	transferring samples between containers
Contamination of;	plastic zip lock bags
	beakers
	plastic containers
Contamination due to;	open air drying
	transport by car and air mail

Additionally, the samples from Upper Shornville are taken from drying beds next to a heavy trafficked road, which may effect the results. Sludge was also let to dry in drying beds and sludge lagoons for various times as well as exposed for different kinds of climate during that time. Further, several different people have handled the samples as they where sent from different institutions, which may give rise to variations. The balance both at UFH and CTH may be poorly calibrated and the ovens used at both institutions may not be totally stable in temperature. Further uncertainties during the laboratorial work at CTH may include:

Spill when;	weighing samples
	transferring samples between containers
Contamination of:	glass wear and other tools used
	coffee grinder
	microwave vessels
	plastic test tubes used in ICP-MS analysis
	steel holders used in LA-ICP-MS analysis
Interference in;	microwave (see section 16.2.1)
	ICP-MS (see section 16.2.2)
	LA-ICP-MS (see section 16.2.3)

The samples may also not have gained 100% TS (Total Solids) before analyzing. Apart for uncertainties related to sampling collection and analysis techniques, the fact that information gathering has been made to large extent by interviews is an additional uncertainties of accuracy.

18. RESULTS AND DISCUSSION

The ICP instrument was used in two ways for analysis. Concentrations were determined with ICP-MS in order to find out the levels of heavy metal in the sludge and compare these to the guideline values of Sweden, this was made only for sample occasion 3 (see table 27) due to limited laboration hours. Data sheets are presented in Appendix 1.

LA-ICP-MS was used for fingerprinting. This was made on all samples collected in the study area as well as for Swedish samples (delivered from SP Sweden) so that a comparison could be made between the two countries. The trend of all metals in the different sludge samples is thereby shown to indicate variations in time and concentrations.

18.1 ICP-MS

Figures 29-32 show the concentrations of heavy metal content found in the sludge collected at the four different sample sites; Dimbaza (D), Zwelitcha (Z), Shornville Upper (SU) and Shornville Lower (SL). Included in these figures are the Swedish guideline values for metal content in sludge to be spread on farmland. The concentrations have been calculated from the ICP-MS results (Appendix 2). Although the concentrations are measured only for sample occasion 3, analysis with LA-ICP-MS justifies for these concentrations to represent all sample occasions (see chapter 16). The standard deviation of the calculated concentrations where below 4 % for all metals apart from Cd where the standard deviation ranged from 15 to 18%.

18.1.1 Cadmium and Zinc

The concentrations of Cd where between 1.1 and 1.9 mg/kg with lowest levels found at Zwelitcha and highest levels found at Shornville (figure 29). It is not surprising that the higher levels are found at Shornville as this station is located in a more developed and trafficked area than that of Dimbaza and Zwelitsha. In developed areas the use of paints and plastics, from which Cd may originate, are naturally more common (see section 12.1). Also, rubber- tires are known to wear off Cd and heavy traffic thereby contribute significantly to Cd levels in the environment. The found concentrations are all below the Swedish guideline value of 2 mg/kg (see section 12.3) and thus of no major concern regarding the use of the sludge as soil improver. One should note however that the standard deviation of these Cd concentrations where as high as 15-18%.

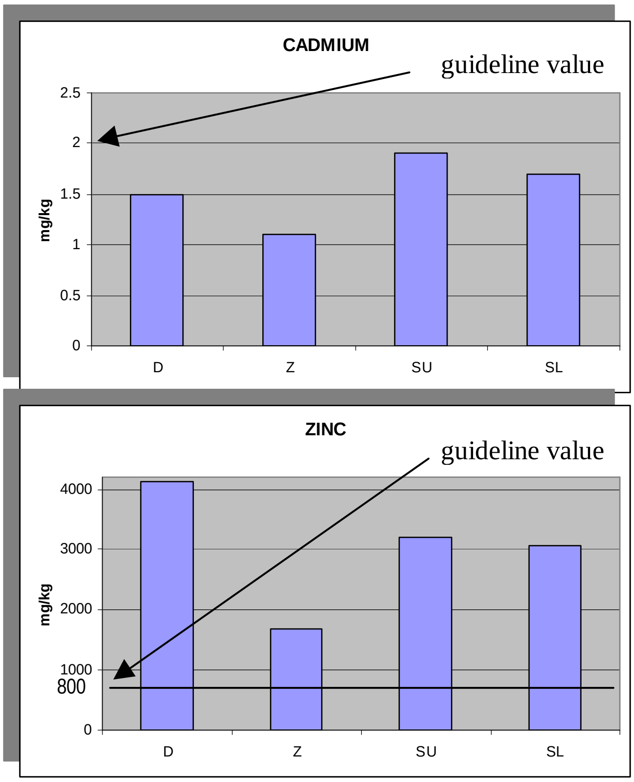

Figure 29 Concentrations of cadmium and zinc at the four sampling stations together with Swedish guideline values.

Concentrations found for Zn are extremely high at all four sample stations (figure 29). Levels range between 1600 mg/kg at Zwelitsha and 4100 mg/kg at Dimbaza. The fact that levels are high at all four stations suggests a common source in the study area. It is not clear what causes the Zn contamination in the study area. The highest Zn-level is found at Dimbaza but all stations have surprisingly high concentrations and further investigation is of great interest. The Zn concentrations found in the study area are double or even five times the Swedish guideline value of 800 mg/kg. In both Zwelitsha and Shornville the sludge is being spread on cultivated land where vegetables including cabbage, carrots, read beat etc. are produced. According to the SEPA (see section 12.3) these values have toxic effect on vegetation and sludge with these levels of concentration should not be spread on farmland. Zn has relatively low toxicity to humans and animals but studies have shown some problems, such as allergies, associated with Zn. Metal accumulation in the soil must also be considered when discussing land application of sludge, as this practice takes place during an extended period of time and these concentrations are highly accumulative even if spread only once per year (web ref 8).

18.1.2 Nickel and chromium

Ni concentrations at Zwelitsha and Shornville are around 37 mg/kg, which is below the Swedish standard of 50mg/kg. In Dimbaza however, high Ni concentration (86mg/kg) is found (figure 30). Looking at the Ni result from the fingerprint analysis with LA-ICP-MS an uncertainty arises regarding these Ni concentrations as the intensities, which indicate concentration, vary greatly for the different sample occations (see figure 37).

As for Cr, Dimbaza again have the highest concentration (195mg/kg), nearly double the Swedish guideline value. Cr-concentrations range between 70 and 120mg/kg for Zwelitsha and Shornville respectively. This makes Zwelitsha being the only plant with Cr concentrations below guideline values. Cr is used in leather industries, which explain the high concentrations found at Shonville (figure 30). In king William's Town the King Tannery recently closed down but obviously left its mark. The elevated concentrations of both Ni and Cr at Dimbaza indicate that the connected industries to this plant include metallurgical and other industries.

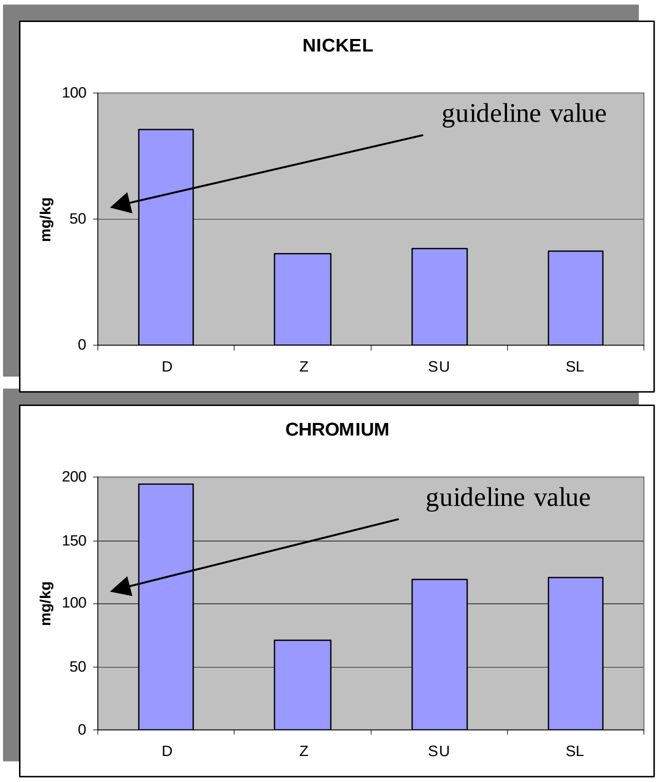

Figure 30 Concentrations of nickel and chromium at the four sampling stations together with Swedish guideline values.

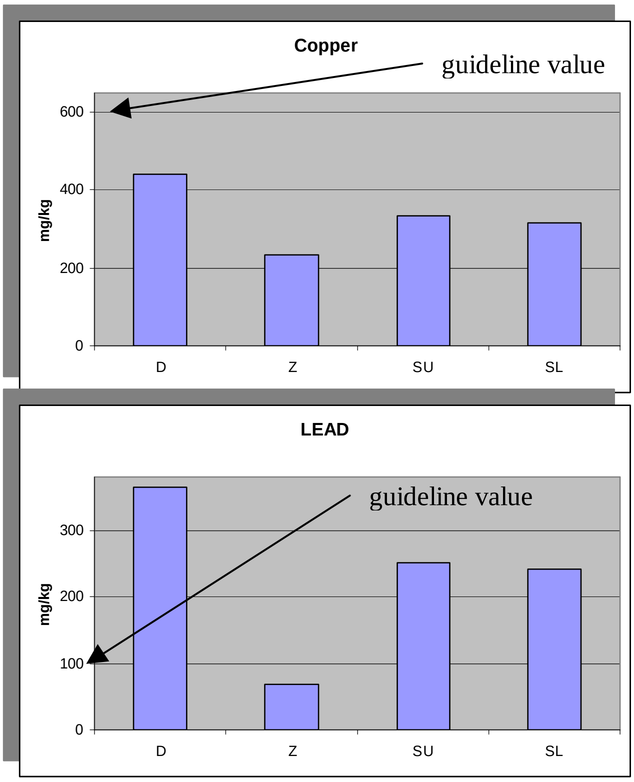

Figure 31 Concentrations of copper and lead at the four sampling stations together with Swedish guideline values.

18.1.3 Copper and lead

Copper concentrations found are between 245 and 441mg/kg at the four sample stations (figure 31). These concentrations are all below the Swedish guideline value of 600mg/kg and thus Cu levels are of no major concern regarding land application. The Cu content in sewage sludge in Sweden is to great extent caused by corroding water pipes. In the study area however, Cu piping is not common and the levels of Cu are attributed to urban runoff. Dimbaza again have the highest concentrations and most likely the connected industries act as an additional source of contamination also for Cu.

It is no surprise to find high concentrations of Pb in a developing region where leaded petrol is commonly used. This analysis shows lowest concentrations for Zwelitsha with 69 mg/kg. This is below the Swedish guideline value of 100 mg/kg. At Shornville (around 245mg/kg) and Dimbaza (365mg/kg) concentrations were extremely high and exceeded the guideline value more than two or even three times (figure 31). As for Shornville the heavy traffic and location in an industrialized surrounding create contaminated runoff that enters the plant. Dimbaza is hardly exposed to any traffic at all but yet has the highest Pb concentration. Again, the industries in the area are the cause of contamination.

Lead is a harmful metal that is toxic and can be accumulated in the human bone marrow as well as cause kidney damage and even acute poisoning. In Shornville it is thus not recommendable to continue using sludge as fertilizer. In the long run concentrations in the soil will accumulate and possibly reach alarming levels, depending on the frequency of land application. Already, the found levels may be toxic to vegetations and microorganisms assuming a mixture of 1 part sludge and 3 parts soil as it is today. Note that again, an uncertainty arises when looking at the result from the fingerprint analysis made with LA-ICP-MS, as the intensities that indicate concentration tend to vary between the different sample occasions for both Cu and Pb (see figure 37 and 42).

18.1.4 Plant by plant

Table 32 show a summarizing overview of issues concerning the three treatment plants included in this case study.

Table 32 Treatment plant summary.

Treatment Plant	*Sludge Collection and/or Treatment*	*Overloaded Plant*	*Metal concentration exceeding guideline values*	*Current sludge use*
Dimbaza Treatment Works	• Secondary settling tanks	NO	Cr, Ni, Zn, Pb	NONE
Shornville Treatment Works	• Liming • Settling tanks	YES	Cr, Zn, Pb	Addition of humus material to soil and fertilizing of low sca farmland.
Zwelitsha Treatment Works	• Primary and secondary settling tanks/humus tank • Biological filter • Digester	NO	Zn	Fertilizing low scale farmland.

Dimbaza

Despite the fact that Dimbaza is located in the rural area outside a township, sludge collected from Dimbaza Treatment Works had a significant problem with heavy metal content compared to what was found in the sludge from the other plants. There is an industrial area with somewhat unknown activities connected to the plant that may very well explain these high levels. Studying the plant and comparing its structure to the other plants' in the study it should be noted that Dimbaza Treatment Works is a small plant with limited sludge treatment yet with high numbers of households connected, which may also affect the sludge quality.

Four out of the six investigated metals exceeded the guideline value given by SEPA for land application use, which proofs the Dimbaza sludge quality non-suitable for land application. It is fortunate that such activities are not taking place. Using this sludge as fertilizer on land where e.g. vegetables for human consumption is being grown may not only damage the crop but put human health at risk due to the characteristics of these metals (see chapter 12). Sustainable use of sludge would in this case rather be production of bricks, as is taking place at other municipalities within the Eastern Cape province. There is a brick factory outside King William's Town that could be contacted in this matter.

Shornville

The sludge in the samples gathered at Shornville Sewage Treatment Works was not as high in heavy metal concentrations as what was found in Dimbaza, however Cr, Zn and Pb exceeded the Swedish guideline values. Levels of Pb are very high and make the sludge non-recommendable for land application but the sludge at Shornville is currently being used as additional humus material on land and as fertilizer for growing maize, carrots and other vegetables. This practice is not taking place to any large extent but yet happening and without the awareness of heavy metal contamination of the sludge. Although the land application may seem useful and successful it is not sustainable to continue with these activities. Metals are accumulating in the soil that in the long run can cause severe contamination in the study area.

At the inlet of the treatment plant lime dosing is taking place mainly to prevent corrosion but liming may also bind certain metals to it and thus have positive results on metal concentrations found. However, the stability of the bounds depends on the surrounding pH levels and the metals may with time be released in the environment due to drop in pH and increase concentrations.

Zwelitsha

The best sludge quality was found in Zwelitsha where Zn is the only heavy metal concentration found exceeding the Swedish guideline values. This is fortunate since Zwelitsha is the plant, out of the three studied, where sludge is being spread on cultivated land to greatest extent.

Land application is not taking place in any organized way by the municipality but local farmers and householders in the surrounding areas come regularly to collect sludge and spread on their vegetable gardens. Zn has relatively low toxicity to humans but the found Zn levels are very high and continuous land application will accumulate Zn in the soil, which is not sustainable.

The reasons the sludge quality is better at Zwelitsha compared to the other plants' is not a surprise as Zwelitsha is located in a rural development area with few industries connected. If this continue being the case in the future and if the extreme levels of Zn can be understood and eliminated, there is a possibility that the sludge from Zwelitsha Sewage Treatment Works can be used as agricultural fertilizer in a sustainable way. This of course demand further investigations of all other aspects than heavy metals regarding sludge used as natural fertilizer.

18.2 LA-ICP-MS / FINGERPRINTS

18.2.1 Trend Analysis

The fingerprints obtained from sludge samples collected both in the study area in South Africa and Sweden are following the same trend extremely well, indicating the characteristics for sewage sludge samples. This is also true for samples taken from different sampling stations in the two countries (Appendix 3). Since fingerprints obtained from various sample occasions follow the same trend it seems to be little variation in metal concentrations over time. This justifies the measured metal concentrations discussed above (see section 18.1); even though concentration measurements have only been performed on one set of samples, e.g. sampling occasion 3, these concentrations are representing the levels of metals during the whole study period.

Looking at the fingerprints obtained from Shornville Lower (SL) there seems to be generally higher values of intensities (concentration) of all the metals measured at one of the sample occasions (figure 32). This is probably due to a matrix effect, e.g. differences within the material analyzed or differences in the compression of the material. Therefore, in further analysis it will be assumed that these values have the same intensity magnitude as the other fingerprints obtained.

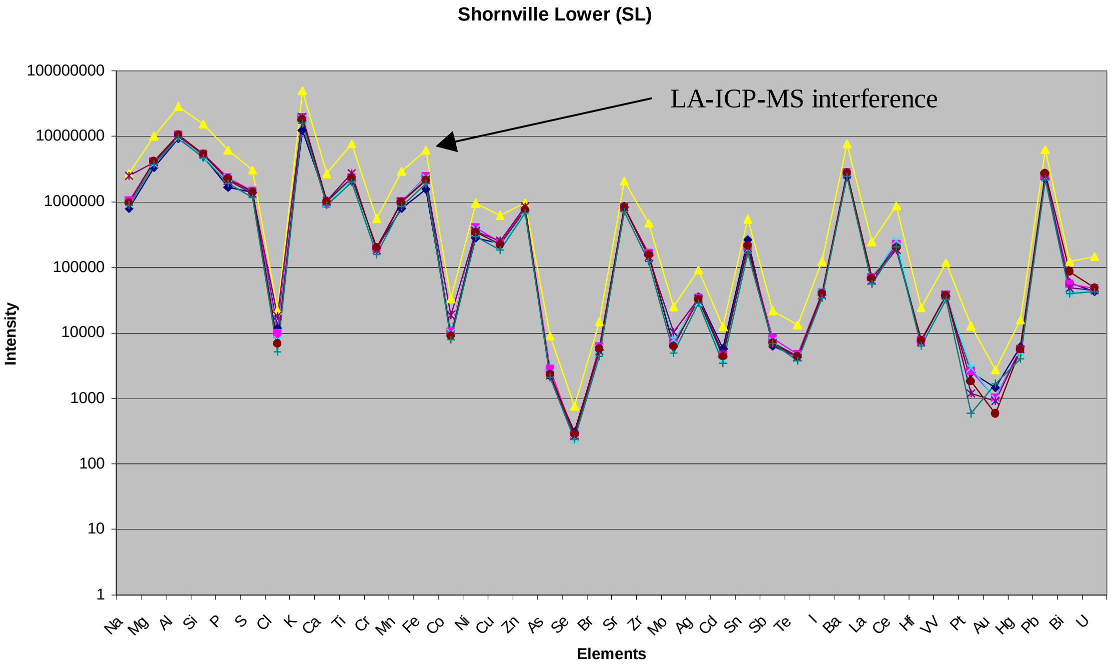

Figure 32. Fingerprints from Shornville Lower (SL). One fingerprint from one sampling occasion has generally higher intensity values due a matrix effect during LA-ICP-MS analyze.

In the following section specific groups of metals will be discusses and a comparison between the fingerprints results from Swedish sewage samples and South African sewage samples will be made. Figure 33 shows a general fingerprint marked with the actual metal groups.

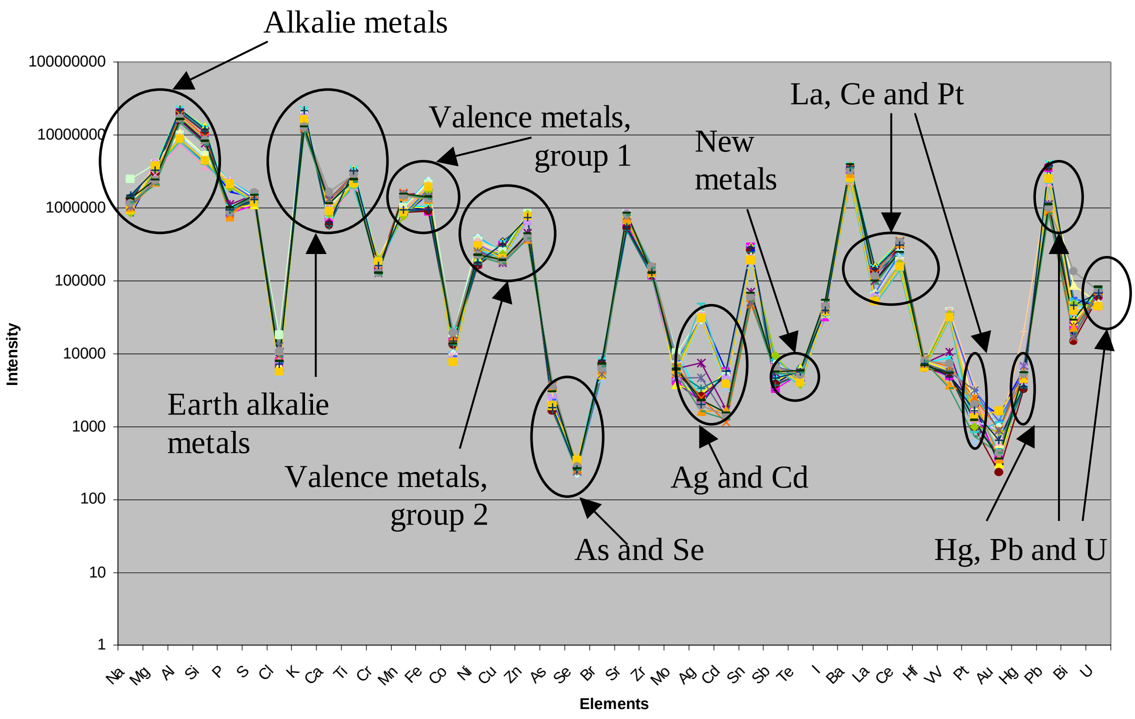

Figure 33. A general fingerprint marked with different metal groups.

The metal groups discussed are:

- Alkali metals; including Sodium (Na), Magnesium (Mg), Aluminum (Al) and Silicon (Si)
- Earth alkali metals; including Potassium (K), Calcium (Ca), Trillium (Ti)
- Valance metals are here divided in to two groups including group 1; Manganese (Mn) and Iron (Fe), and group 2 including; Nickel (Ni), Cupper (Cu) and Zinc (Zn)
- Arsenic (As) and Selenium (Se)
- Silver (Ag) and Cadmium (Cd)
- New metals; including Antimony (Sb) and Tellurium (Te)
- Lanthanum (La), Cerium (Ce) and Platinum (Pt)
- Mercury (Hg), Lead (Pb) and Uranium (U)

18.1.2 Background metals

As explained in chapter 12 levels of background metals may vary between Sweden and South Africa. From the fingerprints gained from the samples in Sweden and the study area in South Africa (figure 34) it can be concluded that the alkali metals (Na, Mg, Al and Si) are present in the same amount both in the Swedish and South African sewage sludge. Levels of Si, however, have somewhat higher intensity (concentration) in the African sewage sludge. The bedrock in the study area mainly contains sandstone, mudstones and shales, thus elevated concentrations of Si is most probably due to the bedrock in the study area.

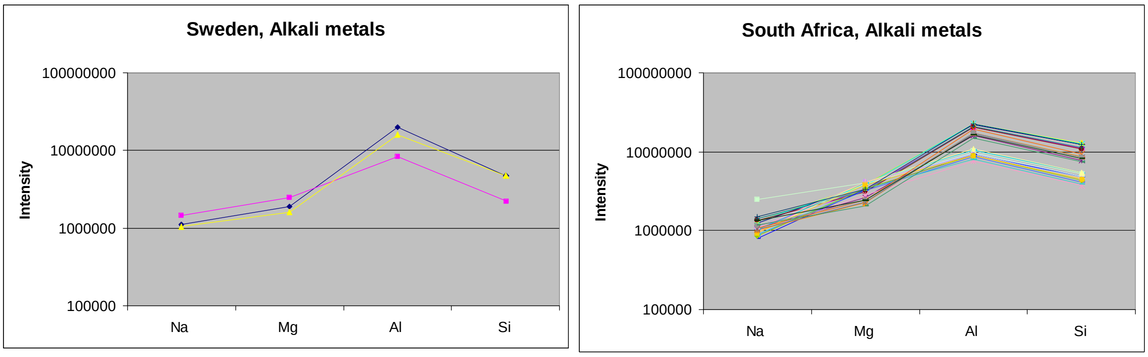

Figure 34. Fingerprints of alkali metals in sewage sludge from Sweden and South Africa.

Among the earth alkali metals (K, Ca and Ti) Ca and Ti follow the same trend and intensity (concentration) in both Sweden and South Africa. The concentration for K in South African sewage sludge is, however, significantly higher then those in sludge samples from Sweden (figure 35). In Sweden the earth layer above the solid bedrock is known to be exceptionally thin compared to the earth layer in other parts of the world including South Africa, which may effect the concentrations of earth alkali metals found. Furthermore the elevated concentration of K in South African sewage sludge may be due to the elite clay present in the study area, which is rich in K.

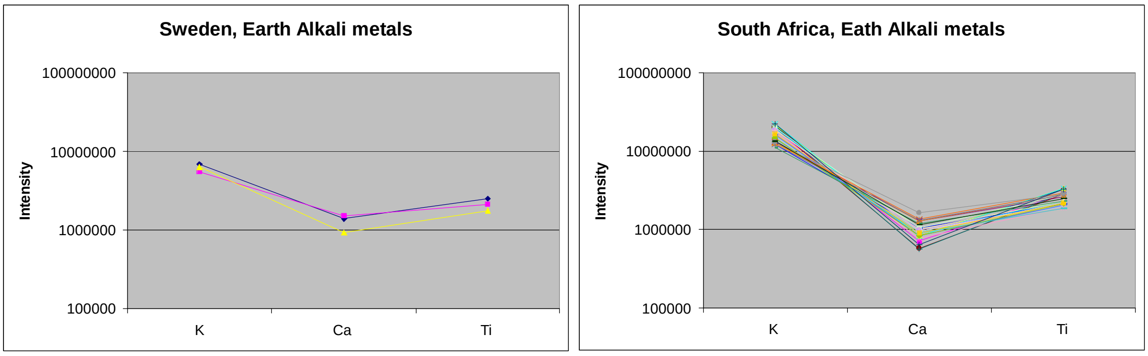

Figure 35. Fingerprints of earth alkali metals in sewage sludge from Sweden and South Africa.

Among the first group of valence metals (Mn and Fe) Mn has a significant lower concentration in the Swedish sewage sludge (figure 36). This is surprising since the Swedish soils mainly constitutes podsol, which is rich in Mn, thus the scenario would rather be the opposite. Figure 36 also show that the level of Fe is higher in the samples obtained in Sweden. In Sweden Fe is used for chemical treatment to large extent in wastewater treatment plants, while this is not true for any of the treatment plants studied in the South Africa. The elevated Fe concentration in the Swedish sewage sludge may also attributed to contamination in the sewage sludge system, e.g. origin from pipe materials etc. It is also possible that elevated Fe levels in Sweden origins from the podsol rich in Fe.

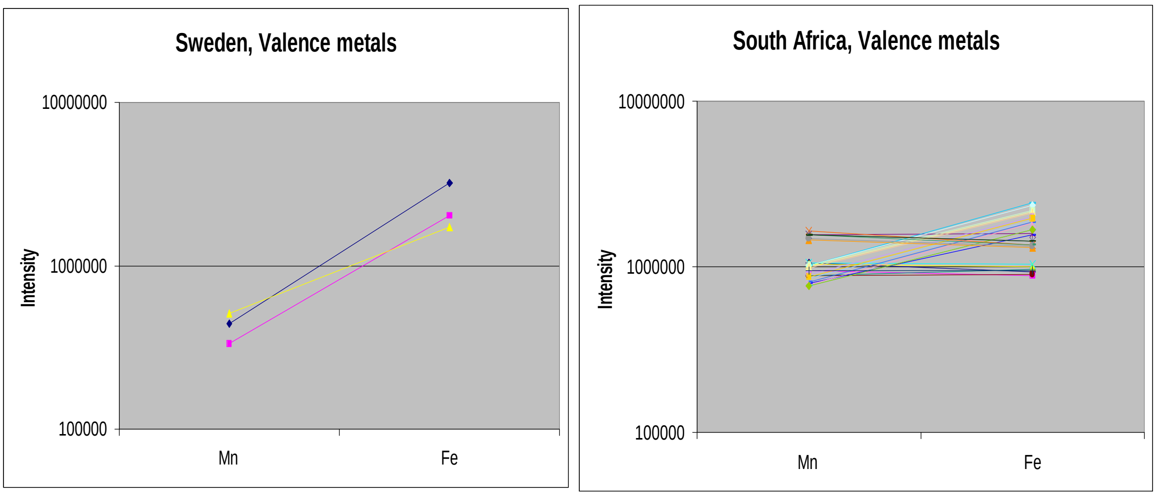

Figure 36. Fingerprints of the first group of valance metals in sewage sludge from Sweden and South Africa.

The intensities obtained for the second group of valance metals (Ni, Cu and Zn) vary greatly between all samples taken both in Sweden and South Africa (figure 37) (see section 12.2). However, Ni concentration in the South African samples was about the same concentration or lower than Ni levels in the Swedish sewage sludge samples. Ni usually follows the same trend as Cr as these metals are commonly used together in different products. This is not the case in this study though as fingerprints from sewage sludge in Sweden show lower concentrations of Cr than those in South Africa (Appendix 4). Furthermore Ni is a common metal in the bedrock in South Africa. This suggests that the higher Ni concentration in the Swedish sewage sludge is due to contamination in the sewer system by urban runoff. It may also originate from the coagulant used in wastewater treatment, where it can be found as a contaminant.

Cu concentrations were expected to be higher in Sweden compared to South Africa, as mentioned in chapter 12, due to contamination in sewer systems in Sweden. Due to the widely spread fingerprints results obtained it is impossible to come to any conclusions whether this is the actual case or not (figure 37). The fingerprints (figure 37) show considerably higher levels of Zn in South Africa compared to Sweden. Zn levels are often connected to levels of Cd as they are often used together in the same industrial production. As will be discussed in section 18.2.4 high levels of Cd can also be found in the South African sewage sludge. Among other factors the elevated levels of Zn may be due to contamination of Cd in the sewer system in South Africa as previously discussed (see chapter 12).

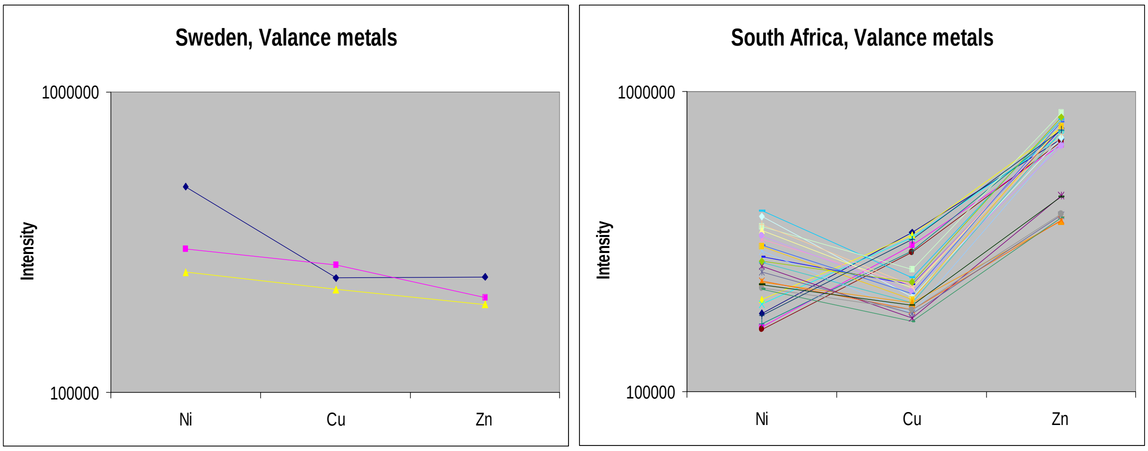

Figure 37. Fingerprints of the second group valance metals in sewage sludge from Sweden and South Africa.

18.2.3 Arsenic and Se

In the case of As and Se concentrations found in sewage sludge in Sweden and South Africa they follow the same trend (figure 38), although the South African sewage sludge seems to have somewhat higher levels. Again the fairly higher concentrations in South Africa may result from the bedrock in the study area.

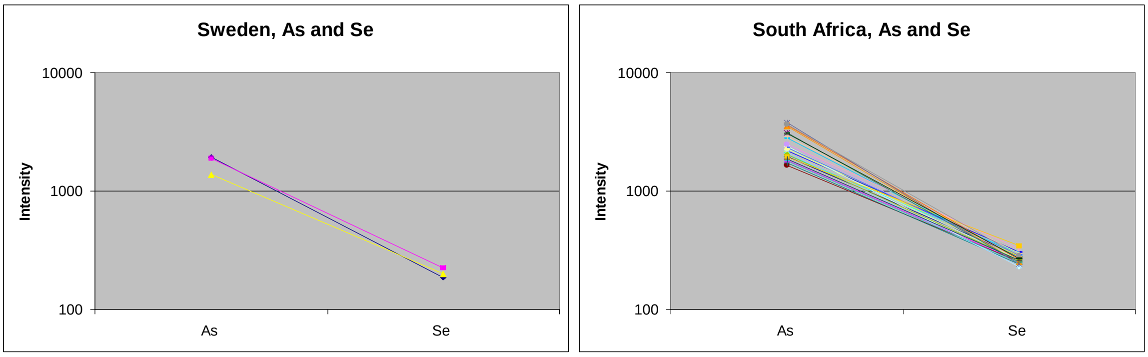

Figure 38. Fingerprints of As and Se in sewage sludge from Sweden and South Africa.

18.2.4 Silver and Cadmium

In the case of Ag and Cd levels found in sewage sludge in South Africa the fingerprint results are widely spread, this creates uncertainties in the conclusion to be drawn (figure 39). In both cases Ag and Cd levels are above the background levels. Somewhat higher concentrations of Cd and Ag can be found in the South African sewage sludge compared to sewage sludge samples from Sweden. Elevated levels of Cd are most probably due to contamination of the sewer system, while high Ag levels probably origin from the current bedrock in the study area. The higher Cd levels in South Africa may also be due to the use of phosphate fertilizers as the study area contains large areas of farming land. In Sweden, and other western countries, Ag originates manly from photographic activities; the number of hobby photographers is however, assumed to be limited in the study area.

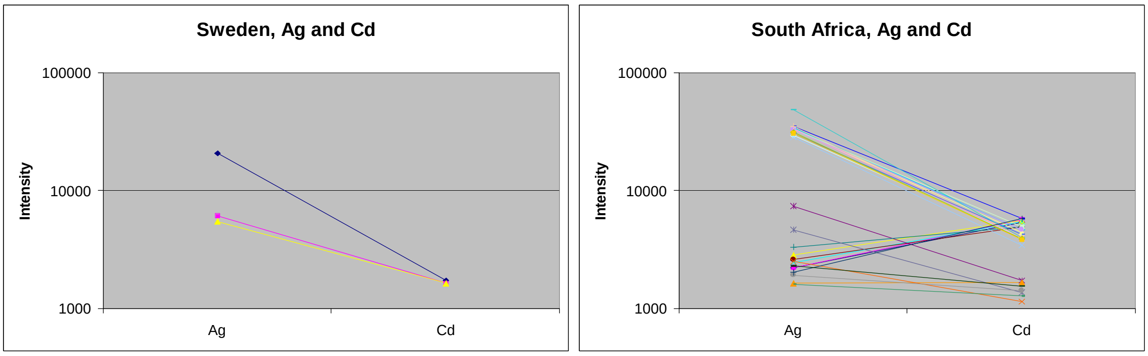

Figure 39. Fingerprints of Ag and Cd in sewage sludge from Sweden and South Africa.

18.2.5 New metals

Sb and Te are often referred to as new metals, which are of concern due to their extended recent use. Neither in sewage sludge from Sweden nor in South Africa have elevated concentrations of the new metals been found (figure 40). From this it can be concluded that these metals have not yet left marks in the environment. Little is however known about the sources to these metals.

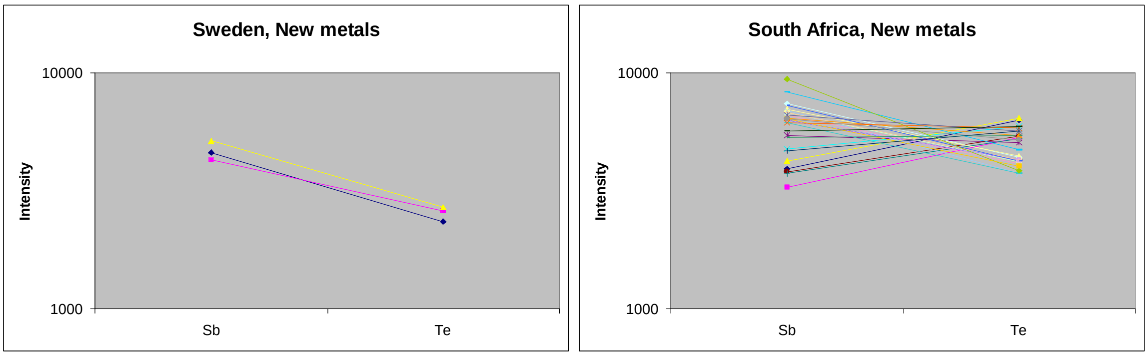

Figure 40. Fingerprints of new metals in sewage sludge from Sweden and South Africa.

18.2.6 La, Ce and Platinum

La, Ce and Pt are metals used in catalytic converters. These metals are known to have high background levels. The fingerprints of La from both Swedish and South African sewage sludge show the same trend and indicate the same concentrations (figure 41). The fingerprints of Ce and Pt shows that higher Ca- and Pt-concentrations are found in sewage sludge from South Africa (figure 41). The source for the high levels of Ce in South African sewage sludge is hard to determine. The higher level of Pt in South Africa can be due to high background levels, since the bedrock in the study area is rich in Pt. The case can also be worsened by Pt mining activities for production of catalytic converters.

Since catalytic converters are not commonly used in South Africa and elevated levels of La, Ce and Pt still are found, it can be concluded that high levels of La, Ce and Pt are not related to the use of catalytic converters. The bedrock composition is therefore likely to be the explanation for elevated La, Ce and Pt concentrations.

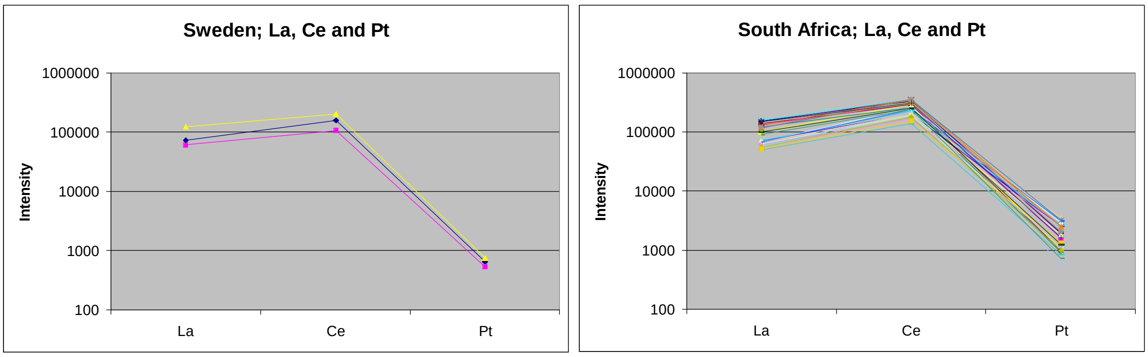

Figure 41. Fingerprints of La, Ce and Pt in sewage sludge from Sweden and South Africa.

18.2.7 Mercury, Lead and Uranium

The fingerprints (figure 42) show higher intensities (concentrations) of Hg in South African sewage sludge. Elevated concentrations of Hg are often a result from acidification fall out. This is not believed to be the case in this study, however, since the ground Sweden is thought to be more acidified. The elevated Hg levels in South Africa may, however, be due to gold extraction activities, thus Hg is commonly used in this process. Even though gold extraction is not practiced in the study area it is known that this is the case for other parts of South Africa, thus Hg can be atmospherically transferred to the study area.

As mentioned in chapter 12 elevated concentrations of Pb are expected to be found in sewage sludge from South Africa, thus leaded petrol is of more common use. The fingerprint results confirm this hypothesis (figure 42). Due to the lesser amount of cars present in South Africa, especially in the rural parts of the study area, the indication is not as large as it would have been if the two countries were fully comparable.

The fingerprints obtained of U found in sewage sludge in Sweden and South Africa shows that elevated concentrations of U are found in Swedish sewage sludge (figure 42). This is expected since the Swedish bedrock is rich in U as it is consisting of mainly granite (see section 12.2).

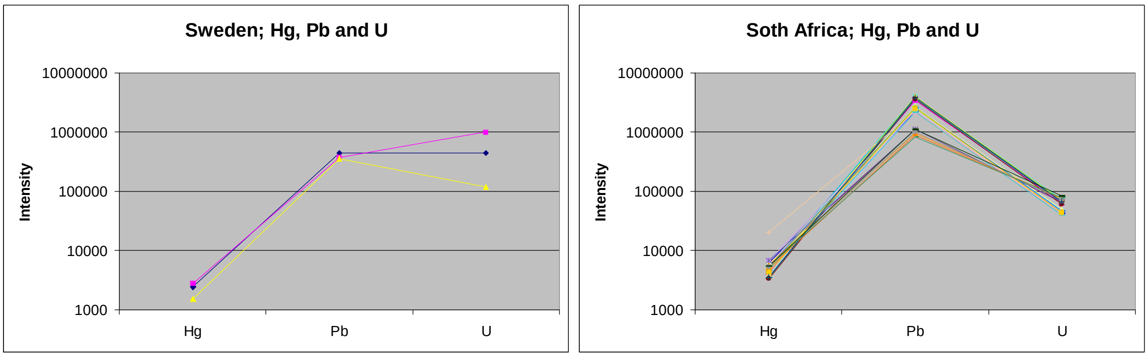

Figure 42. Fingerprints of Hg, Pb and U in sewage sludge from Sweden and South Africa.

19. CONCLUSIONS

This study was carried out in order to determine the sludge quality regarding metal content in sewage sludge from the Eastern Cape in South Africa. Sewage sludge was collected on a weekly basis from three different treatment works (Shornville Sewage Treatment Works, Zwelitsha Sewage Treatment Works and Dimbaza Sewage Treatment Works) in South Africa during a seven-week period. The South African sewage sludge samples were also compared to three different sewage sludge samples available from Sweden. An investigation of possible sustainable sludge use in the study area in South Africa, with special attention on the use of sludge as agricultural fertilizer, was also carried out.

Metal concentrations were determined with ICP-MS in order to find out the levels of heavy metals (Chromium (Cr), Cadmium (Cd), Zinc (Zn), Lead (Pb), Cupper (Cu), Nickel (Ni)) in the South African sewage sludge and compare these to the guideline values of Sweden. LA-ICP-MS was used for fingerprinting of 37 different metals. This was made on the samples collected in the study area in South Africa as well as for Swedish samples so that a comparison could be made between the two countries. The trend of all metals in the different sludge samples is thereby shown to indicate variations in time and concentrations.

The concentration analysis showed that despite the fact that Dimbaza Sewage Treatment Works is located in the rural area outside a township, sewage sludge collected from the plant had a significant problem with heavy metal content compared to what was found in the sludge from the two other plants. There is an industrial area with somewhat unknown activities connected to the plant that may very well explain these high levels. The fact that Dimabza Sewage Treatment Works is a small plant with high numbers of households connected may also affect the sludge quality. Four metals (Zn, Ni, Cr and Pb) out of the six investigated metals exceeded the Swedish guideline values for land application use, which proofs the Dimbaza sewage sludge quality non-suitable for land application.

The sludge in the samples gathered at Shornville Sewage Treatment Works was not as high in heavy metal concentrations as what was found in Dimbaza, however Cr, Zn and Pb exceeded the Swedish guideline values, with Pb levels far above the guideline value. It can therefore be concluded that the sewage sludge produced at Shornville Sewage Treatment Works is not recommendable for land application. Since the sewage sludge at Shornville is currently being used as additional humus material on land and as natural fertilizer, metals are accumulating in the soil. This may in the long run cause severe contamination in the study area.

The best sludge quality with regards to metals was found at Zwelitsha Sewage Treatment Works where Zn is the only heavy metal found at concentration exceeding the Swedish guideline values. The relatively good sludge quality is explained by the fact that Zwelitsha is located in a rural development area with few industries connected. The very high Zn levels indicate that the current land application of the sewage sludge is not sustainable as Zn is being accumulated in the soil. If the extreme levels of Zn can be eliminated however, there is a possibility that the sludge from Zwelitsha Sewage Treatment Works can be used as agricultural fertilizer or other land applications.

The fingerprints obtained from sludge samples collected both in Sweden and the study area in South Africa follow the same trend extremely well, indicating the characteristics for sewage sludge samples and little variation in metal concentrations over time.

Among the alkali (Sodium (Na), Magnesium (Mg), Aluminum (Al) and Silicon (Si)) and earth alkali metals (Potassium (K), Calcium (Ca) and Trillium (Ti)) similar Na, Mg, Al, Ca and Ti concentrations in sewage sludge were found both in the Swedish and South African sewage sludge samples. The levels of Si and K were, however, higher in South African sewage sludge due to the bedrock (mainly sandstone, mudstones and shales) and soil (elite clay) in the study area.

Neither of the valance metals (Mn, Fe, Ni, Cu and Zn) is present in the same levels in Sweden and South Africa. Mn has lower concentrations in the Swedish sewage sludge, while the level of Fe is higher in the samples from in Sweden. In Sweden Fe is used as a treatment chemical to high extent in wastewater treatment plants, while this is not true for any of the treatment plants studied in the South Africa, thus elevated concentrations of Fe are found in Swedish sewage sludge. Ni concentration in the South African samples was somewhat lower than Ni levels in the Swedish sewage sludge samples, although Ni is common bedrock metal in South Africa. This suggests that the higher Ni concentration in the Swedish sewage sludge is due to contamination in the sewer system by urban runoff. It may also originate from the coagulant used in Swedish wastewater treatment, where it can be found as a contaminant. The difference in Cu levels was impossible to explain as the fingerprint results varied greatly. Considerably higher levels of Zn were found in South African sewage sludge compared to Swedish sewage sludge. Among other factors the elevated levels of Zn may be related to contamination of Cd in the sewer system in South Africa, thus Zn and Cd are often used together in the same industrial production.

In the case of As and Se concentrations found in sewage sludge in Sweden and South Africa they follow the same trend, although the South African sewage sludge seems to have somewhat higher levels. Again the fairly higher concentrations in South Africa may result from the bedrock in the study area.

Levels of Ag and Cd found in the Swedish and South African sewage sludge are both above the background levels. Somewhat higher concentrations of Cd and Ag can be found in the South African sewage sludge compared to sewage sludge samples from Sweden. Elevated levels of Cd are most probably due to contamination of the sewer system, while high Ag levels probably origin from the current bedrock in the study area. The higher Cd levels in South Africa may also be due to the use of phosphate fertilizers as the study area contains large areas of farming land. In Sweden, and other western countries, Ag originates manly from photographic activities; the number of hobby photographers is however, assumed to be limited in the study area.

La, Ce and Pt are metals used in catalytic converters. These metals are known to have high background levels. The fingerprints of Ce and Pt shows that higher Ca- and Pt-concentrations are found in sewage sludge from South Africa, while La are present in the same concentration. The source for the high levels of Ce in South African sewage sludge is hard to determine. The high levels of Pt in South African sewage sludge may be due to high background levels, since the bedrock in the study area is rich in Pt. The case can also be worsened by Pt mining activities for production of catalytic converters. Since catalytic converters are not commonly used in South Africa and elevated levels of La, Ce and Pt still are found, it can be concluded that high levels of La, Ce and Pt are not related to the use of catalytic converters.

Elevated concentrations of Hg were found in South African sewage sludge. The elevated Hg levels in South Africa may be due to gold extraction activities, thus Hg is commonly used in this process. The use of leaded petrol may be the cause of the higher concentrations of Pb found in South African sewage sludge. Higher levels of U were found in the Swedish sewage sludge, thus the Swedish bedrock is rich in U as it is consisting of mainly granite.

20. RECOMMENDATIONS

To be able to use sludge as agricultural fertilizer it is necessary to fully evaluate the quality of sludge. This study focuses on metals, which make only one out of many steps in the path towards sustainable use of sludge in the Eastern Cape. Whenever a study like this is made new issues arises and ideas evolve, thus the following recommendations are given:

- A measurement campaign that is stretching over a longer time period needs to be done in order to give more accurate evaluation of the sludge quality and be able to draw substantial conclusions.
- Regarding the use of the sludge as fertiliser it is essential to look at the sludge quality from other points of view than metal content, such as pathogens, persistent organic pollutants (POP:s), nutrient content, sludge texture etc.
- The measurement campaign in this study does not include mercury (Hg) measurements. It is, however, recommended that this matter should be evaluated.
- It is clear that it is a problem with zinc (Zn) levels in whole study area. It is of major importance to evaluate and eliminate this in order to make use of the sludge in the future.
- Other possibilities for making use of the sludge should be further looked into, such as brickproduction, landfilling etc.
- The sludge quality at Dimbaza need to be further evaluated and it is essential that something is done to reduce the high levels of metals in the sludge.
- The grit that is buried in the ground at Dimbaza is most probably causing contamination of surrounding soil. This should therefore be stopped as soon as possible.
- The sludge that is currently used as fertilizers is not used in a sustainable way and it is possible that further use can cause hazardous effects both on plants and humans.

In the future, with increased urbanization, there is an evident need to move towards and integrated effluent disposal system. It is known that the municipality is discussing to reroute the wastewater infrastructure in the future. Most likely this will include a regional sewage treatment works to serve Bisho, King Williams Town, Ilitha, Zwelitsha, Breidbach and other settlements in the same area (figure 15). Such reconstruction provides a great opportunity to start making use of the separate sewage system that currently exists but not in use. Furthermore there are several advantages in implementing a regional wastewater treatment scheme. Firstly, by virtue of the size of the works, the treatment process operates more tolerantly and is not subject to large variations of load. This makes it easier to achieve an effluent of the required standard. Secondly a single regional works, preferably located away from populated areas, is far more desirable than a number of small works each located adjacent to the community it serves.

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APPENDIX

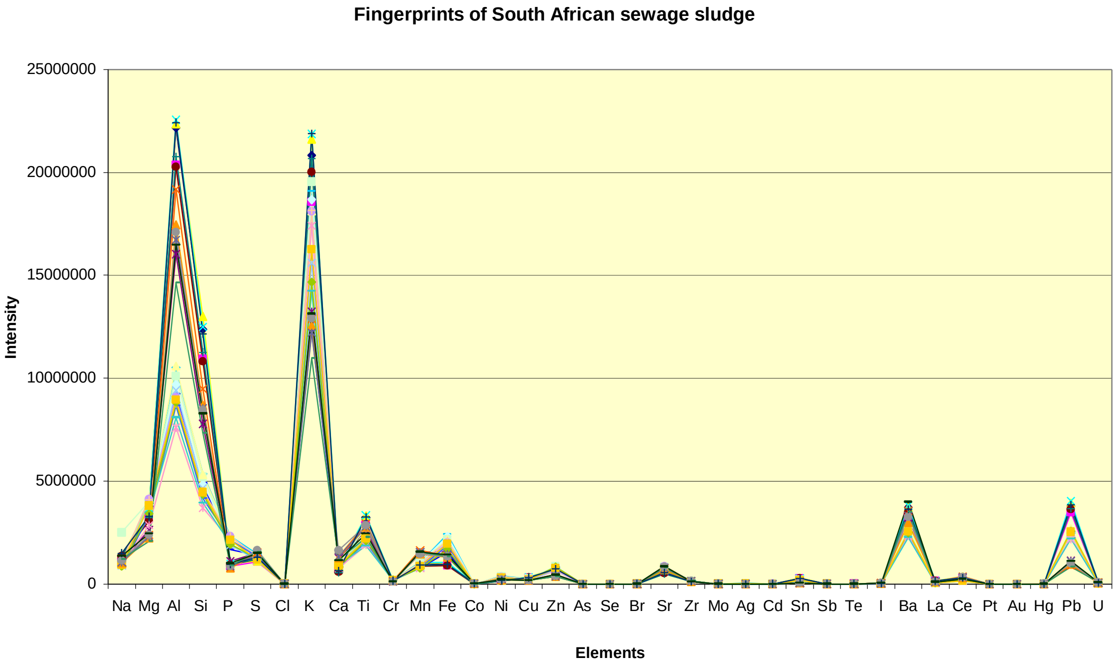
Appendix 1. Sample details

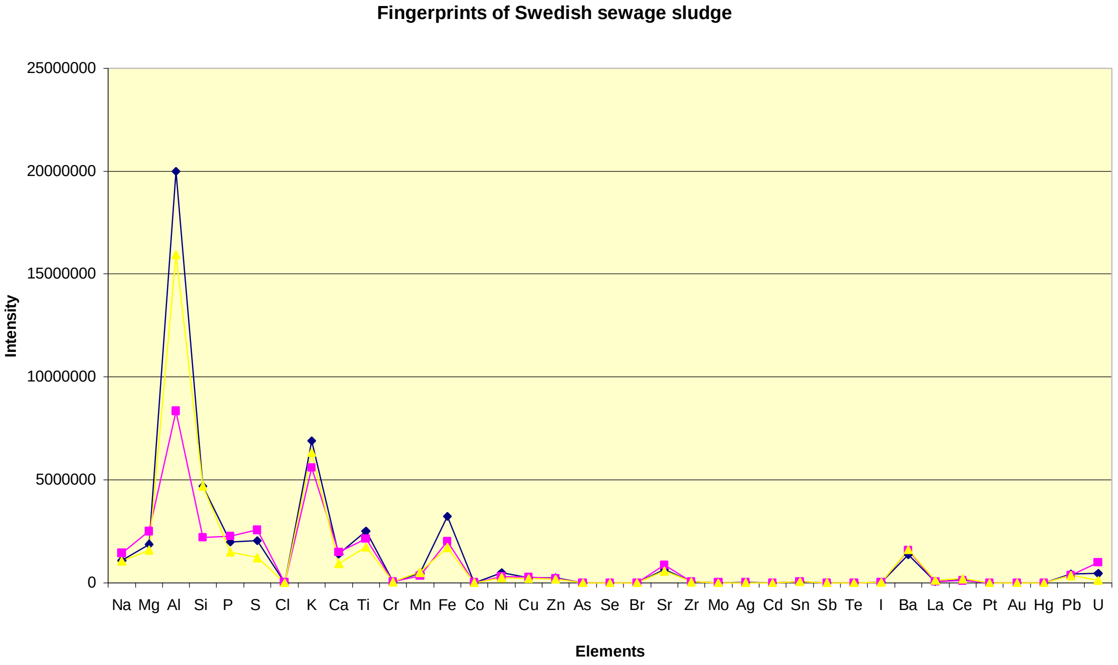
Sample	*weight before drying in oven (g)*	*open air drying (hrs)*	*time in oven (hrs)*	*weight after drying in oven (g)*
31-Oct				
SU1	26.56	0	40	23.39
SL1	27.4	0	40	31.93
D1	35.72	0	40	31.61
Z1	49.51	0	40	32.6
6-Nov				
SU2	42.88	0	110	13.34
SL2	44.19	0	110	15.43
D22	42.97	0	110	19.02
Z22	44.58	48	64	22.1
12-Nov				
SU3	50	0	110	15.72
SL3	42.99	0	110	14.81
D3	38.99	0	110	17.14
Z3	34.7	48	64	18.84
19-Nov				
SU4	54.64	48	64	36.51
SL4	38.99	48	64	26.36
D4	52.76	48	64	32.2
Z4	45.49	0	110	26.05
26-Nov				
SL5	42.67	88	96	23.00
SU5	39.44	88	96	22.26
Z5	39.57	88	96	17.73
D5	50.86	88	96	30.64
3-Dec				
SL6	37.37	88	96	19.23
SU6	37.64	88	96	21.28
Z6	40.04	88	96	20.10
D6	33.57	88	96	11.63
6-Dec				
SL7	34.76	88	96	18.18
SU7	42.56	88	96	23.95
Z7	43.93	88	96	21.65
D7	47.9	88	96	33.78

Appendix 2. Heavy Metal concentrations in sludge samples from the study area

Station	Element	Concentration mg/kg	standard deviation
D	Cd	1.5	0.1
	Cr	195.0	2.3
	Ni	85.7	4.2
	Cu	441.6	10.7
	Zn	4118.1	54.5
	Pb	364.8	9.7
Z	Cd	1.1	0.2
	Cr	70.8	3.5
	Ni	36.5	1.0
	Cu	235.4	42.0
	Zn	1680.6	13.1
	Pb	69.1	2.9
SU	Cd	1.9	0.3
	Cr	119.0	4.8
	Ni	38.2	0.9
	Cu	332.8	4.4
	Zn	3197.7	16.8
	Pb	251.4	1.3
SL	Cd	1.7	0.3
	Cr	121.0	2.7
	Ni	37.5	0.3
	Cu	317.3	2.0
	Zn	3059.7	63.3
	Pb	241.4	2.1

Appendix 3. Fingerprints of South African and Swedish sewage sludge





The graphs show fingerprints from all stations in South Africa and Sweden.

Appendix 4. Cr-fingerprints of South African and Swedish sewage sludge