THE DESIGN AND ASSESSMENT OF AN INTEGRATED MUNICIPAL WASTE BENEFICIATION FACILITY: TOWARDS IMPROVED SEWAGE SLUDGE MANAGEMENT IN DEVELOPING COUNTRIES

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ABSTRACT

This research aimed to firstly confirm the hypothesis that the current management of sewage sludge generated during the treatment of wastewater in the Eastern Cape Province of South Africa is poor and, as such, this material poses a threat to local environmental and human health. Secondly, through a rational design approach, the current research also aimed to design and assess the suitability of a novel integrated process incorporating appropriate technologies for improved sewage sludge management. The lack of an appropriate tool for the assessment of the integrated process necessitated the development of an appropriate technology assessment (TA) methodology based on environmental, technical, social and economic criteria. A combination of informal participatory methods such as semi-structured interviews and formal research methods including questionnaires, risk assessment exercises and laboratory analyses were used. Based on the above it was estimated that 116 tons dry sludge were generated in the province per day and that the concentration of heavy metals present in the sludge was generally within the limits for reuse on agricultural land. Furthermore the sludge from all sample sewage treatment works (STWs) was found to be free of any detectable pathogens. Despite the above, a preliminary risk assessment and chemical analysis revealed that existing sludge management practices at sample STWs posed a threat to the environment, particularly to water resources and exacerbated the problems associated with the discharge of poorly treated municipal wastewater. The root causes of the poor sludge management were considered to be a lack of non-regulatory incentives and financial resources. Highly integrated ecologically engineered systems were thought to offer a solution to the dual problem of poor sludge management and municipal effluent treatment, while providing necessary economic incentives. To facilitate the design of a system appropriate to local conditions, it was necessary to first develop a rational design methodology, which incorporated a detailed TA step. The result of the design process was an Integrated Waste Beneficiation Facility (IWBF) that incorporated a number of process units comprised of appropriate technologies including composting, vermicomposting, algal ponding technology and aquaculture. A detailed TA indicated that the benefits of the proposed IWBF would, at the majority of sample sites, outweigh the potential negative impacts and it was thus recommended that investigations should continue on pilot-scale facilities. Furthermore, although the proposed TA based on four sustainability criteria categories was thought to provide a more accurate assessment of the true sustainability of a technology, the acquisition of information was problematic highlighting the need to re-think current TA methodologies and to address associated constraints allowing the tool to be used and fully comprehensive.

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LIST OF ABBREVIATIONS

AA specs	Atomic Absorption Spectrometry
AIPS	Advanced Integrated Ponding System
ASP	Algal Settling Pond
BOD	Biological Oxygen Demand
CEFIC	European Chemical Industry Council
C:N	Carbon to Nitrogen Ratio
CTSA	Cleaner Technologies Substitute Assessment
DEAT	Department of Environmental Affairs and Tourism
DNH & PD	Department of National Health and Population Development
DWAF	Department of Water Affairs and Forestry
EC	Eastern Cape
ECA	Environmental Conservation Act
EnTA	Environmental Technology Assessment
g	Gram
GDP	Gross Domestic Product
GNP	Gross National Product
HRAP	High Rate Algal Pond
IDC	International Development Corporation
IDP	Integrated Development Plan
IWBF	Integrated Waste Beneficiation Facility
IWMP	Integrated Waste Management Plan
Kg	Kilogram
MDGs	Millennium Development Goals
ML	Megalitre
MP	Maturation Pond
MSWM	Municipal Solid Waste Management
MWMS	Municipal Waste Management System
N	Nitrogen
NEMA	National Environmental Management Act
NIOSH	National Institute for Occupational Safety and Health
NMMM	Nelson Mandela Metropolitan Municipality
NWMS	National Waste Management Strategy
OECD	Organisation for Economic Corporation and Development
P	Phosphorus
PCBs	Polychlorinated biphenyls
PAHO	Pan American Health Organisation
PFP	Primary Facultative Pond
PUDSS	Permissible Utilisation and Disposal of Sewage Sludge
R	South African Rand
RDP	Reconstruction and Development Program
SEI	Stockholm Environmental Institute
STWs	Sewage Treatment Works
TA	Technology Assessment
TCLP	Toxicity Characteristic Leaching Procedure
TDS/day	Tonnes of Dry Sludge per Day
UNEP	United Nations Environment Program
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
USEPA	United Stated Environmental Protection Agency
WHO	World Health Organisation
WRC	Water Research Commission

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CHAPTER 1

GENERAL INTRODUCTION

1.1. SUSTAINABLE DEVELOPMENT AND WASTE MANAGEMENT IN DEVELOPING COUNTRIES

For a long time, prevailing rural economies and low population densities kept pollution and waste-disposal localized and prevented spread into the wider environment. With modest human consumption levels and no centralized systems with drains to convey wastes like sewage, the rivers and coastal zones remained comparatively free of anthropogenic pollution. In addition, the absorption capacity of the natural environment was adequate to deal with such modest pollution loads (Brown & Jacobson, 1987; Wong *et al*., 1997). However, urbanisation and economic development are now changing the face of the earth dramatically and remain powerful drivers of pollution. Between 1970 and 2000, the global population doubled (from 3 to 6 billion), the degree of urbanisation in developing countries doubled from about 25% to 50% and these countries' economies grew tenfold from US$0.4 to 4 trillion (WHO, 2004). Industrial cities with factories are the engine for economic development, but also consume more resources and use up more space forcing all waste to be discharged into the "nature" beyond these city's borders (Viessman & Hammer, 1993). The pollution load into the environment has increased concomitantly, to the point that in many places nature cannot cope any longer with these pressures and the very basis of several economic activities has become threatened (Eckenfelder, 1989; Wong *et al*., 1997; Chara *et al*., 1999).

The Commission on Sustainable Development, at its second session in 1994, expressed great concern over current patterns of development, utilization and management of water resources (UNEP, 1999). Subsequently it requested a comprehensive assessment of the world's freshwater resources. The results showed that current patterns of water use in developing countries, countries with economies in transition and industrialized countries alike are often not sustainable (Wright, 1999). There was mounting evidence that the world faced a worsening series of local and regional water quality problems, partly as a result of unregulated effluent disposal especially in poor developing countries (Grau, 1994; Chara *et al*., 1999; Lier & Lettinga, 1999). The key role of sustainable water management for poverty eradication was

one of the key outcomes of the World Summit on Sustainable Development (2002) and the plan of implementation outlined several central statements related to freshwater and sanitation issues including the following:

- To halve by the year 2015, the proportion of people without access to safe drinking water;
- To halve by the year 2015, the proportion of people who do not have access to basic sanitation;
- To develop integrated water resources management and water efficiency plans by 2005, with support to developing countries;
- To support developing countries and countries with economies in transition in their efforts to monitor and assess the quantity and quality of water resources.

However, according to Borge Brende, Chair of the 12th Session of the UN Commission for Sustainable Development, "*The global target of halving the proportion of people without access to basic sanitation by 2015 is currently out of reach for many countries*". Current projections indicate over 2 billion people will still not have access to any type of improved sanitation facility by 2015. In sub-Saharan Africa the number of people without sanitation coverage will almost double by 2015 if current rates of progress are maintained (WHO, 2004). Inadequate sanitation is also holding up other health-related Millennium Development Goals including access to clean drinking water, child mortality and universal primary education. An estimated 1.2 billion humans live worldwide without access to clean drinking water, more than 1.7 billion do not have appropriate sanitary facilities and approximately 80% of all diseases and a third of all deaths are caused by inadequate water and lacking hygiene in developing countries (WHO, 2004). This is a tragedy that has been called "*the 'silent emergency' a global crime against humanity*" (BBC, 2004).

Pollution of the environment and in particular of water resources as a result of poor waste management including sanitation constitutes one of the most immediate and serious environmental problems facing governments around the world, but specifically in developing countries.

1.1.1. "Waste management" in developing countries

According to White & McDougall (1998), the phrase "waste economy" can be used to emphasize that wastes arise from the processes of extraction, production and consumption of

materials and goods, and as a result waste management must be understood in the context of the socio-economic system. Digregorio (1993) stated that "*waste management consists of much more than the regulations put in place by national, state or local government authorities*" (i.e. municipal waste management system (MWMS) or firms under contract to them), whose responsibilities include storage, collection, transportation and disposal of these wastes. In many countries, the MWMS only handles a minor fraction of the wastes generated by its citizens. Due to this short fall, the conventional MWMS approach has failed to provide efficient and effective services to residents in most countries (Digregorio, 1993). Doberstein (1992) estimated that between 30-75% of waste in the cities of developing countries goes uncollected. In some countries wastes are burned, buried or simply dumped onto vacant land or into drains, ditches and other waterways because of inadequate collection or options for its disposal. The gradual but irrevocable deterioration of the water resources across the globe strongly remind us that it is not enough to dispose of wastes from our cities. Proper collection and disposal of both solid and liquid wastes is essential in order to control the transmission of waterborne diseases and to prevent degradation of the environment and surface waters (Grau, 1994; Gijzen, 1998; Williams, 1998). Curi (1985) emphasised that, *"If we do not manage our wastes properly from a holistic environmental point of view, we stand to lose the future"*.

The prevalence of parasites, tetanus, malaria, hookworm, cholera and diarrhoea in most African cities is attributed to unsanitary conditions (Stephens & Harpham, 1992). Songsore & McGranahan (1993) revealed that malaria, diarrhoea, intestinal worms and upper respiratory tract infections were among the most common health problems reported at out-patient facilities in the Greater Accra Region of Ghana. In the city of Accra, the major health problem was disease attributed to poor environmental sanitation, which was exacerbated by ignorance and poverty. In Tanzania, Yhdego & Majura (1988) reported that poor sanitation and improper waste disposal practices resulted in the spread of infectious diseases, which were the most frequent causes of morbidity and mortality. In 1994, 61 960 cases of cholera resulting in 4 389 deaths were reported in Angola, the Democratic Republic of the Congo, Malawi, Mozambique and Tanzania (WHO, 1995). Another 171 000 cases of dysentery with at least 600 deaths were reported in Malawi, Mozambique and Zimbabwe (Holloway, 2002). In 1999, Zambia experienced a cholera outbreak recording more than 11,000 cases and at least 390 deaths. Recently in September 2005, South Africa also experienced highly publicised cases of

a cholera outbreak in the Tshitava village in Limpopo and a typhoid outbreak in Delmas in Mpumalanga both of which were primarily as a result of poor waste management. In the typhoid-stricken town of Delmas an underground lake which feeds the reservoirs in the area became infected with *E.coli* resulting in 116 confirmed cases with 2 reported deaths and more than 700 other people suffered from diarrhoea (DNH & PD, 2005). In November 2005, the South African government was struggling to contain an outbreak of cholera that had stricken more than 15, 000 people along the country's eastern coast. More than 450 people were hospitalized with illness and 59 people had already been killed.

From the above, it appears that in the majority of developing countries, poor solid waste management and inadequate sewage treatment pose serious threats to human health and the environment. Most developing countries do recognize the need for improved waste management, but they are faced with a number of constraints which hamper effective and efficient waste management efforts. These are discussed in Section 1.2 below.

1.2. CONSTRAINTS TO WASTE MANAGEMENT IN DEVELOPING COUNTRIES

The trend in the industrialized countries is towards further development and improvement of waste disposal systems, which require highly skilled labour, large amounts of capital and steady socio-economic conditions to ensure adequate financial and treatment supplies for operation. Although this conventional approach is the standard in the industrialized countries, its application as a standard solution for developing countries is not feasible (UNEP, 1998a). In most developing countries, waste treatment and disposal is a matter of concern that needs to be addressed, but the countries' prospects for economic and social development, poverty and priorities for industrial investments form obstacles in making decisions about public waste facilities. Considering these, some of the constraints they face include:

1.2.1. Economic

One of the key constraints to addressing waste management in developing countries is simply the cost involved in the process (Briscoe & Garn, 1995). According to the World Bank (1999), "*only about 3% of a country's gross national product (GNP) can realistically be spent on environmental protection, which comprises among others water supply and pollution*

control". In addition, the low priority attached to the waste management sector in developing countries means that the levels of services required for protection of public health and the environment are often not attained (Wong *et al*., 1997). This problem is acute at the local government level where local taxation systems are often inadequately developed and, therefore, the financial basis for public services, including waste management, is weak. This weak financial basis can be supplemented by the collection of user service charges (Thurgood, 1998). However, users' ability to pay for these services is very limited in poorer developing countries, and their willingness to pay for these often irregular and ineffective services is not high either.

In addition to limited funds, many governments in developing countries lack good financial management and planning. The World Bank (1999) found that in a town of a developing country, over 90% of the annual budget provided for waste management was used up within the first six months. This lack of financial management and planning, particularly cost accounting, depletes the limited resources available for the sector even more quickly, and causes waste management services to halt for some periods, thus losing the trust of service users. The World Bank (1999) report went on to state that, "*waste management and in particular sewage treatment costs are often under-estimated, whether they relate to low-cost on-site options in poorer urban neighbourhoods, construction and operation of sewers and sewage treatment plants, or to investments in industrial pollution abatement*". Wastewater sewering and treatment tend to be two to three times more expensive than the costs to abstract, treat and distribute tap water (UNEP, 1998a). Many decision makers overlook the fact that the capital investment in infrastructure such as a wastewater treatment plant is equally expensive as keeping that facility operating and maintained, yet the latter is far less popular. Treatment plants also generally consume a lot of energy, generate large quantities of excess sludge that must be disposed of, and apply relatively sophisticated equipment that demands well-trained operators and engineers.

According to the World Bank (1999), "*It can be argued that countries need a GNP above US$ 2, 200 per capita to finance sanitation, basic wastewater collection and treatment across their territory. In 1997, 4 billion people lived in low-income countries with an average GNP per capita below US$ 1,400. Therefore, only the 1.5 billion people in higher income countries with a GNP per capita above US$ 3, 125 (the World Bank classification for middle and high-*

income categories) could in principle meet this requirement". So does this mean that no progress can be made in developing countries? Industrialized countries have tried to provide external support to developing countries. However, for some donor agencies, waste management may not be a priority sector for support. As a result, there is a finite amount of funds that can be allocated to the sector. Furthermore, because of its inherent nature, waste management, does not easily generate revenues (Digregorio, 1993) and this is particularly true in developing countries where the willingness and ability to pay for waste management services are low. Therefore, for external lending agencies, this means that the risk of providing a loan to such projects is generally high.

The economic constraints to waste management discussed above clearly highlight the importance for developing countries to develop waste management initiatives and technologies that have built-in revenue raising/generating systems in order to allow wastes to be able to pay for themselves, and to decrease the reliance of waste management initiatives on local taxation systems or user service charges.

1.2.2. Institutional

In the majority of developing countries several agencies at the national level are usually involved, at least partially, in waste management. However, there are often no clear roles/functions of the various national agencies defined in relation to waste management and often no single agency or committee designated to coordinate their projects and activities (DEAT, 2000). The lack of coordination among relevant agencies often results in different agencies becoming the national counterpart to different external support agencies for different waste management projects without being aware of what other national agencies are doing. This leads to duplication of efforts, wastage of resources, and unsustainability of waste management programs. The lack of effective legislation for waste management, which is a norm in most developing countries, is partially responsible for the roles/functions of the relevant national agencies not being clearly defined and the lack of coordination among them. In addition, legislation related to waste management in developing countries is usually fragmented, with several different laws including some clauses related to waste management (Glazewsky, 2000). It should also be noted that legislation can only be effective if it is enforced, which does not often happen in developing countries. Therefore, comprehensive

legislation, which avoids the duplication of responsibilities, fills in the gaps of important regulatory functions, and is enforceable, is required for sustainable development of waste management systems in developing countries.

The institutional constraints to waste management discussed above, indicate that the "command and control" approach to waste management is not effective and has a number of weaknesses the main one being the inability of authorities to enforce the legislation. For this reason, developing countries should seek to improve and develop waste management systems that involve non-regulatory incentives.

1.2.3. Technology

"*Practical solutions to current environmental problems show that the technical answer is not always the whole answer*" (Zavadska & Knight, 2002). In many situations this is partly due to inadequate detailed technical knowledge and partly to socio-economic reasons. A lack of information be it scientific or social is a common phenomenon in many developing countries. This problem is directly applicable to municipal waste management systems, many of which do not have formal methods of managing their wastes and whose systems are often unstructured, inadequate or obsolete. In addition, in most developing countries, there is typically a lack of skilled human resources with the technical expertise necessary for waste management planning and operation. According to Zavadska & Knight (2002), "*many officers in charge of solid waste management, particularly at the local level, have little or no technical background or training in engineering or management*". Without adequately trained personnel, a project initiated by external consultants cannot be continued. Therefore, the development of human resources in the recipient country of external support is essential for the sustainability of such collaborative projects. Alternatively, effective technologies need to be developed to match existing skills levels.

There is also a lack of overall plans for waste management at the local and national levels in developing countries. As a result, a waste technology is often selected without due consideration of its appropriateness in the overall waste management system. In some cases, foreign assistance is given to a component of a waste management system for which the use of resources may not be most cost-effective. For instance, an external support agency can provide its support to improve a general disposal site. However, if the coverage of a solid

waste collection service is so low that the solid waste generated is dumped at undesignated sites (e.g., open areas, water channels, streets, etc.), improving the disposal site would have little impact on the overall solid waste management effectiveness. In such a case, the low collection coverage would be a bottleneck in the overall solid waste management system in the city, and it would be most cost-effective to provide resources to upgrade the collection service (Zavadaska & Knight, 2002).

The lack of research and development activities in developing countries also leads to the selection of inappropriate technologies in terms of local climatic conditions, financial and human resource capabilities, and social or cultural acceptability. Very often aid is given for "hardware" machines and equipment designed in developed countries ultimately resulting in selection of a technology that can never really be used and in so doing, wasting the resources spent and making the project unsustainable. Several guides/manuals on appropriate waste management technologies in developing countries are available in the literature (WHO, 1989; Wong *et al*., 1997; UNEP, 1999) and the selection of technology could be made sometimes based on these guides/manuals. However, in most cases, these guides/manuals must be modified to the local conditions prevailing in the country, and therefore local studies are normally still needed. Such studies can be relatively easily incorporated into a collaborative project and, to the extent possible, should involve local research institutions (UNEP, 1998b).

The technical constraints to waste management discussed above clearly highlight the importance for developing countries to conduct proper assessments prior to implementation of waste management technologies by carrying out needs analyses, locating appropriate solutions and then conducting technology assessments on these solutions. A needs analysis will allow governments to obtain waste technologies based on the waste management needs of the citizens in a given country whereas technology assessments will provide governments with the information they require in order to make informed decisions regarding imported technologies or to assess alternative technologies that have been developed to match existing skills levels. Technology assessments are discussed more extensively in Chapter 4 of this thesis.

1.2.4. Health

Promoting the reuse of waste in cultivation on a large scale in areas with high population concentrations, as is the case in most developing countries raises the issue of health impacts. This fundamental issue was brought up by the Ad Hoc Panel of the Advisory Committee on Technology Innovation for the Board on Science and Technology for International Development of the National Research Council (USA) in 1981who proposed that, "*The strongest negative factor in the use of wastes particularly human and animal wastes for the production of food, feed or fertilizer is the possibility of disease transmission, which would negate the gains derived from the use of the waste"* (US NRC, 2002). The issue of health is critical. Solid waste in developing countries contains large quantities of pathogens due to the presence of human excreta, and the application in farming of such untreated waste can pose significant health risks both to those who have direct contact with it, and the general public, who can be affected through food chain links (Furedy *et al*., 1997).

1.2.5. Social

The social status of waste management workers is generally low in both developed and developing countries, but more so in developing countries (World Bank, 1999). This owes much to a negative perception of people regarding work which involves the handling of waste and can lead to disrespect for the work and in turn results in poor work ethic of laborers and poor quality of their work. In any country, developed or developing, there are social or cultural norms accepted by the society and such norms affect the design of waste management systems. Where the society allows only a certain social class or group to deal with solid waste, the availability of a work force for solid waste collection and disposal is constrained (Ayres, 1996). In some countries, directly handling human waste is a traditional taboo, which then prohibits the application of co-composting of refuse and human waste.

There is often a lack of understanding of local cultures and ways of life by external support agencies and this has often been the cause for the failure of collaborative projects (White & McDougall, 1998). Because of insufficient resources available in the government sector, collaborative projects often have attempted to mobilize community resources and develop community self-help activities. Results are a mixture of success and failures with the latter often being the result of a lack of economic as well as social incentives to participate in waste

management activities. The social incentive is based on the responsibility of individuals as part of the community for the improvement of the community, and is created by public awareness and school education programs. The lack of public awareness and school education about the importance of proper waste management for health and well-being of people severely restricts the use of community-based approaches in developing countries (Joubert *et al*., 1991; Wong *et al*., 1997; Bryceson & Bank, 2001; Melford, 2003).

From the discussion above it is clear that all these constraints need to be considered in the design phase of any waste management strategy in any developing country, and the necessary data with regards to the nature of the waste management problem needs to be collected through detailed research programmes. Alternative solutions should be tested using technology assessments which take into account the environmental, economic, social and technical sustainability and implications of selected waste management strategies in order to determine their suitability to address specific problems. Section 1.3 of this thesis provides a detailed discussion of waste management and waste management problems facing South Africa, which has been selected as a focus for the study since there has been significant policy development related to waste management in this country.

1.3. WASTE MANAGEMENT IN SOUTH AFRICA

1.3.1. Introduction

According to the DEAT (1999), "*South Africa is a country that is slowly emerging from a period of unsustainable and inequitable development, the likes of which have not only had significant economic and social impacts, but also resulted in serious environmental degradation*". In the past, waste management in South Africa was not afforded the priority it warranted as an essential function required to prevent pollution, while at the same time promoting environmental protection and public health. Consequently, insufficient funds and human resources were allocated to this function (DEAT, 2000). In many instances this neglect resulted in a lack of long term planning, a lack of information, a lack of appropriate legislation and a lack of capacity to manage the waste stream. An example of the lack of long term waste planning was the failure to make provision for waste processing and disposal sites in physical land use and development decision-making. "*The lack of information is manifested in insufficient data on waste generators, waste generation and waste disposal sites, which*

make waste management difficult" (DEAT, 1999) and environmentally and socially unacceptable standards currently characterize many aspects of waste management, particularly in rural areas, where services are often non-existent. In many urban communities (which have always had poor quality services), these services have collapsed as a result of non-payment, poor budgeting and financial planning (World Bank, 1999).

Some of the consequences of previous waste management policies are continued air, land, fresh water and marine pollution, resulting in the disruption of ecosystem processes (DEAT, 2000). Although there are many problematic wastes in South Africa, the poor management of sewage and related material (sewage sludge) seems to be having significant negative impacts on the water resources of the country not to mention human health (Fatoki *et al*., 2003). This is one of the reasons why the current study chose to primarily focus on investigating the production, treatment and disposal of municipal wastewater and management of sludge.

Although South Africa is extraordinarily rich in natural resources, the fresh-water resources of the country are under stress and increasing demand for water and the pollution of ground and surface water resources make careful water and waste management a priority (DEAT, 2000). Typical pollutants of South Africa's freshwater environment include industrial effluents, domestic and commercial sewage, acid mine drainage, agricultural runoff, and litter. According to Neytzell-De Wilde (1992), rivers of the Western Cape, Eastern Cape, KwaZulu-Natal and the Vaal River in the Orange Free State have significant problems with total dissolved solids. Most of South Africa's rivers also have eutrophication problems some of which have resulted from poor effluent disposal by sewage treatment works (STWs). A Council for Scientific and Industrial Research (CSIR) report in 1991 confirmed earlier studies undertaken in the 1970s indicating that the quality of many water sources in South Africa is declining, primarily as a result of eutrophication and pollution by trace metals and micro-pollutants (Neytzell-De Wilde, 1992).

Marx *et al*. (2004) found that the total mass of untreated sewage sludge to be disposed of on a daily basis from the 900 registered STWs in South Africa was an estimated 1 750 T DS/D for undigested sludge and 1 375 T DS/D for digested sludge. This large amount of sludge places increasing pressure on the country's landfills. DEAT (1999) predicted five of the nine

provinces will have landfill shortages within the next decade. Of further concern is the low percentage of hazardous waste that is properly disposed of i.e. at permitted, environmentally acceptable landfill sites, or treatment facilities. Increasing amounts of land set aside for landfills could also lead to habitat destruction and species loss.

South Africa's re-integration into the global economy and international political arena necessitated an improved pollution and waste management system (DEAT, 2000). International concern around increasing pollution has escalated over the past 20 years, and is highlighted in over 17 international conventions, 4 protocols, 3 treaties and 2 agreements all dealing with waste management (Glazewsky, 2000). One of the most important conferences held as a result of concern about global environmental issues was the United Nations Conference on Environment and Development (UNCED), held in Rio De Janeiro in 1992. Consequently, 178 countries agreed on Agenda 21 as a blueprint for sustainable development and the White Paper on Integrated Pollution and Waste Management is part of the South African government's efforts to meet the goals of Agenda 21 (DEAT, 2000). It states that "*part of effecting a transformation to sustainable development is for South Africa to redefine the way in which pollution and waste is managed*" (DEAT, 2000). South Africa's focus on integrated waste management is also emphasised by the fact that municipalities now have to prepare an Integrated Waste Management Plan (IWMP) as part of the operational strategies of their Integrated Development Plan (IDP). This requirement brings integrated waste management down to the local level, where it has the greatest potential to make an impact on society and the environment (DEAT, 2000).

In an attempt to meet the sanitation-related Millennium Development Goals, South Africa and other developing countries are likely to face considerable challenges with regards to the management of two main waste types, namely municipal wastewater and its related solid residue, sewage sludge. This is because a certain proportion of basic needs will likely be met through a centralised sewage treatment system and will therefore involve the establishment of conventional waterborne sanitation technologies. One of the products of these technologies will be sewage sludge and the volume requiring management in order to prevent harm to human health and the environment is likely to increase as a direct result of trying to achieve the above mentioned goals. Research into the improved management of sewage sludge should

thus be regarded as a priority. Before proceeding, the nature and current disposal of this material needs further discussion.

1.4. PRODUCTION, TREATMENT AND DISPOSAL OF SEWAGE SLUDGE

1.4.1. Definition of sewage sludge

Sewage sludge is the solid, semi-solid and liquid material produced at several stages of wastewater treatment (Jimenez *et al*., 2002). It is considered to be a hazardous waste because it contains a number of components such as organic matter, bacteria, viruses, heavy metals and nutrients which may have significant adverse effects on human health and the environment (Horan, 1990). Sewage sludge has a wide range of physical, chemical and biological properties and according to its origin and type, sewage sludge is made of a complex mixture of compounds. Primary and waste-activated sludge are voluminous mainly because they contain large quantities of water in addition to the solids removed during the treatment process (Burgess & Stuetz, 2002). The typical concentration of solids in primary sludge is 4-8%, in waste-activated sludge 0.5-1.5%, and in waste-activated and primary sludge combined 3-6% (Jimenez *et al*., 2002). However, when primary sedimentation is excluded from the activated sludge process (such as in extended aeration systems), the concentration of waste-activated sludge is slightly higher and is between 0.8 and 2% (Horan, 1990).

1.4.2. Production of sewage sludge

When raw sewage is delivered via sewers, to a treatment works it contains an appreciable amount of floating materials (such as wood, paper, rugs, plastics and faecal material) as well as heavier solids such as grit and large suspended solids (Horan, 1990). In order to prevent damage to mechanical equipment such as pumps and aerators as well as blockage of pipes and valves, these solids have to be removed at an early stage in the treatment process. To achieve this, sewage is simply passed through a series of screens and strainers (Zavadska & Knight, 2002). This is known as ‘preliminary treatment’ and generates small quantities of residuals. However, sewage that has been subjected to preliminary treatment will still contain a high concentration of ‘settleable solids’ and primary sedimentation tanks are used to remove these. Three types of sedimentation tanks are routinely employed at treatment works and these are designed according to their flow regime (horizontal flow tanks, radial flow tanks and upward flow tanks). Extensive details each of these sedimentation tanks can be found in Horan

(1990). Primary treatment generates a large amount of primary sludge that is removed periodically from the bottom of the sedimentation tanks together with minor quantities of oil, grease, and scum skimmed from the top of the tanks. This step also results in the separation of wastewater into two different streams, each of which goes to a different secondary treatment step (Figure 1.1).

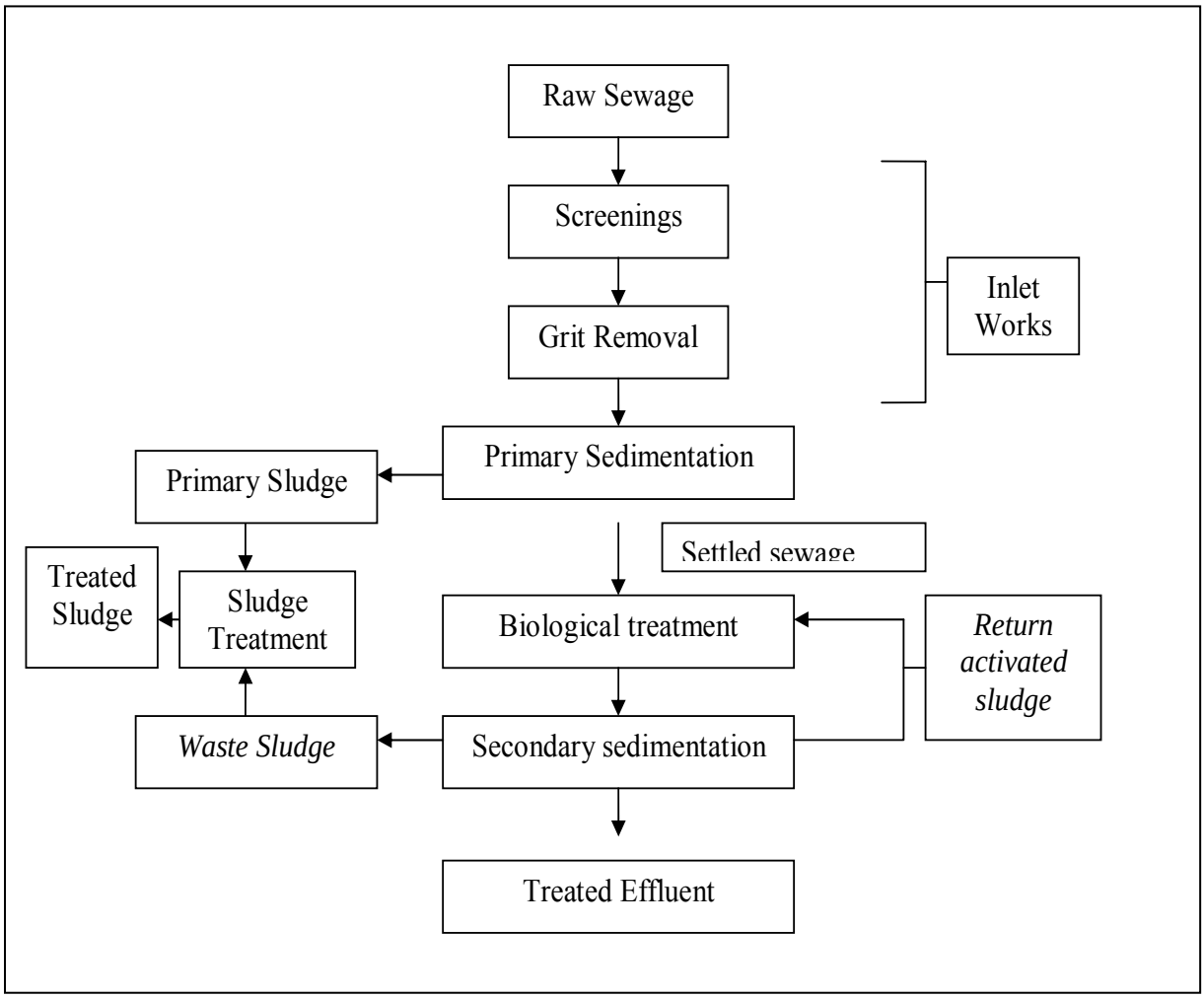

Figure 1.1: Schematic diagram of a Conventional Activated Sludge Plant

(Source: Horan, 1990)

Due to the physical-chemical processes involved in wastewater treatment, the sludge stream tends to concentrate heavy metals and poorly biodegradable trace organic compounds as well as potentially pathogenic organisms (viruses, bacteria etc) present in wastewaters (Murray, 2000). Untreated sewage sludge has relatively high levels of disease-causing microorganisms (pathogens) and is decomposable (or unstable). The unstable nature of untreated sewage

sludge can generate odours and makes it attractive to disease-carrying vectors such as insects, rodents, and birds. Therefore, further treatment of sludge is needed to reduce pathogen levels and vector attraction. These sludge treatment processes are typically based on one or more of the following approaches: application of high temperature, application of chemical disinfectants, reduction of the microbial food source in sewage sludge (measured as the volatile organic content), or removal of nearly all moisture from the sludge. For example, aerobic and anaerobic digestion are common methods of treating sewage sludge that reduce its volatile organic content and simultaneously apply heat (Arther *et al*., 1981; Alaerts *et al*., 1990; Horan, 1990; Hall, 1992; Jimenez *et al*., 2002; Marx *et al*., 2004). Provided below is a discussion on some of these sewage sludge treatment technologies.

1.4.3. Sewage sludge treatment technologies

According to Zavadska & Knight (2002), "*the most neglected aspect of wastewater treatment is the treatment and disposal of its main by-product- sludge and technologies for low-cost and sustainable treatment of sludge are still mostly lacking*". Sludge, which accounts for less than 1% of the wastewater flow, represents 50% of the treatment cost and 90% of the day-to-day problems for plant operators (Alaerts *et al*., 1990; Horan, 1990).

There are several ways to treat sludge including conventional and advanced treatment steps. Conventional treatment includes stabilization (in order to reduce biodegradability and potential to cause nuisance) and dewatering (reduce transport cost), while advanced treatment includes sludge disinfection (reduce or prevent health hazards) (Jimenez *et al*., 2002). Approximately 79% of the sludge produced in the European Community (amounting to 4.38 millions tonnes per year) is treated before disposal (Odegaard *et al*., 2002). However, unlike the European Community, most developing countries including South Africa do not monitor or keep records of the amount of sludge they treat before disposal. A discussion on a number of common sludge treatment processes follows.

1.4.3.1. Thickening

The purpose of thickening processes is to increase the solids concentration in the sludge by reducing its water content. Thickening equipment will increase the solids content to between 2 and 5% (Marx *et al*., 2004) and will decrease the capital and operating costs of subsequent

sludge processing steps by substantially reducing the volume. Thickening is usually accomplished by gravity, dissolved air flotation or centrifugation. Gravity thickening is by far the most commonly practiced internationally (Jimenez *et al*., 2002). Thickening waste-activated sludge, for example, can increase the concentration of solids from 0.5-1.5% to 2-3% (Horan, 1990).

1.4.3.2. Stabilization

Sludge treatment also includes stabilization, which destroys volatile organic matter to minimize bad odours and reduce the number of pathogens. Studies on the capacity of living of the pathogens and parasites found in sludge like helminth eggs confirmed the resistance of the eggs to most biological treatments such as aerobic stabilization, mesophilic anaerobic digestion and lagooning (Hays, 1977; Arther *et al*., 1981; Dominguez *et al*., 1997). After applying other biological and chemical treatments (composting, liming) the viability of the parasite eggs clearly showed the necessity of precisely defining the process parameters (temperature, pH, homogenization, treatment time, end process heat value etc) in order to efficiently destroy the helminth eggs. It is generally demonstrated that heat is a powerful virus killer. Thermophillic aerobic digestion and pasteurization remain attractive processes to inactivate viruses and other pathogens (60^0C for a treatment contact time superior or equal to an hour). Thermal conditioning processes have been used in South Africa but are not popular due to negative aspects such as high operation and maintenance costs and the treatment requirements for the dewatering liquors (Marx *et al*., 2004). Stabilization also reduces the volume of sludge because some of the organic solids are destroyed in the process (Hall, 1992). Stabilization is usually followed by a dewatering step.

1.4.3.3. Dewatering

This is primarily a physical operation that separates the liquid and solid portions of the dilute sludge generated during the precipitation/clarification process. By increasing the solids content of the sludge, the volume is reduced, which in turn reduces transportation and often disposal/recovery costs. Dewatering is usually performed in a series of steps utilizing two or more pieces of equipment (Odegaard *et al*., 2002). Dewatering can be accomplished by natural methods or by mechanical means. Natural methods include sludge drying beds and lagoons although this requires long periods of time. Faster and smaller, but also more cost

intensive, are machine processes such as vacuum filters, pressure filters, belt filter presses and centrifuges (Marx *et al*., 2004). According to Odegaard *et al*. (2002), "*for the choice of the correct dewatering process it is important to consider a multiplicity of further boundary conditions such as quantity, structural situation, disposal, regulations, availability and personnel*".

1.4.3.4. Conditioning

Mechanical dewatering can be aided by chemical conditioning of the sludge prior to dewatering which may raise the concentration of solids up to 35-40%. Chemical conditioning entails dosing sludge with chemicals such as ferric chloride, aluminium sulphate, lime or poly-electrolytes. Conditioning with polyelectrolyte can be found at most dewatering installations that employ centrifuges or filter belt presses (Marx *et al*., 2004). The main advantage of chemical conditioning is that it improves sludge settling and dewatering characteristics and the main disadvantage is that the chemicals are relatively expensive (Horan, 1990).

Sludge treatment technologies employed at STWs vary according to the proposed method of final disposal and use. However, the costs of these operations also play a very important role in the type of treatment technologies selected and in so doing affect the quality of sludge generated. In South Africa, a sludge management decision matrix has been developed by the Water Research Commission (Marx *et al*., 2004) and it relates established end-use options (e.g. incineration, agricultural use etc.) to required sludge treatment steps and the established technologies available under each treatment step. For example, sludge to be used for land application to natural veld and tree plantations must have limited metal and inorganic contents as outlined in the Permissible Utilisation and Disposal of Sewage Sludge (PUDSS) document (Department of Agriculture *et al*., 1997) and must have undergone treatment such as alkaline stabilisation, composting, pasteurisation or thermal conversion in order to reduce the numbers of pathogenic organisms. Extensive details on the sludge management decision matrix can be found in Marx *et al*. (2004).

Following treatment, there are a number of disposal options for the treated sludge and these are discussed in Section 1.4.4 that follows.

1.4.4. Sewage sludge disposal techniques

Due to the large volumes of sludge generated during wastewater treatment and the potentially hazardous nature of the materials contained in it, the production and disposal of sewage sludge is a worldwide concern. However, differences in geography and politics have meant that different approaches to sludge management have been emphasized in different parts of the world (Zavadska & Knight, 2002). Nevertheless, in contrast to sewage treatment, the disposal of sludge in cities of developing countries has received very little attention (Strauss *et al*., 1999). The cost of sewage sludge disposal is an expense incurred by operators of wastewater treatment plants and depends on the quality and quantity of organic substances, heavy metals and other pollutants in the sludge. Stringent environmental regulations in most countries have led to the application of improved high-standard technologies for wastewater treatment often with a consequent rise in the cost of municipal wastewater treatment. For example, some environmental regulations stipulate that wastewater should be biologically purified which inevitably leads to increased costs and subsequently increased sewage sludge production (Leschber, 1997). Due to the increased production of sludge, sewage sludge is often discharged in an uncontrolled manner into receiving waters, or onto vacant plots and when sludge is disposed of on vacant plots serious problems arise due to the shortage of disposal capacity and leaching of heavy metals to underground water, surface water and soil (Marchioretto *et al*., 2002).

1.4.4.1. Disposal into large water bodies

Mankind has always found it convenient to dispose of untreated wastes to rivers and oceans, although the former quickly became untenable as the limited water flow resulted in catastrophic effects such as anoxia and death of fish (Marshall, 1988). Sludge dumping is a major component of waste disposal to the ocean and is coming under increasingly close scrutiny because of possible adverse environmental effects. This development is perhaps best illustrated by the moves of the US Environmental Protection Agency which has placed a ban on ocean dumping of sludge (Marshall, 1988) since 31 December 1998. Disposal of sludge to surface waters was also no longer permitted in the European Union under the Urban Waste Water Treatment Directive and other countries are slowly phasing it out. The banning of ocean disposal of sludge certainly has ramifications for coastal cities e.g. Sydney and Brisbane in Australia. Land disposal remains a simple, safe and available option, however,

this situation could change with increasing development and the main factors affecting ocean disposal need to be fully understood (Cabelli, 1983; Balkas & Juhasz, 1993; Carter & Howsam, 1998). Disposal of sewage sludge to the marine environment is still permissible in South Africa and the majority of developing countries.

The main advantage of ocean disposal of sludge is its simplicity and consequent low cost, although the latter may be disregarded if deep sea dumping is required (Kudo & Miyahara, 1991). Furthermore, marine disposal can potentially fix carbon dioxide - as carbonate in sediment (Odegaard *et al*., 2002). There are, as already mentioned, a number of components of sewage sludge which have the potential to cause problems particularly in the ocean environment. These components include organic matter, oil and grease (especially hydrocarbon residues) bacteria and viruses, heavy metals, organo-chlorines and nutrients. Negative impacts include the depletion of available oxygen as a result of rapid bacterial metabolism of organic matter present in sludge (Zobell, 1946; EMECS, 1990; Gunnerson & French, 1996), environmental hazards resulting from oil and grease in sludge accumulate to form floating grease balls protecting bacteria and viruses (Gunnerson & French, 1996), pathogen transmission to infants (0-4 years) who bathe in lightly polluted waters (Feachem *et al*., 1983; Fattal *et al*., 1986; Shuval *et al*., 1986), bioaccumulation, whereby heavy metals present in sludge are concentrated through the marine food web. E.g. the notorious Minimata Bay incident (Kudo & Miyahara, 1991), where very large quantities of easily assimilable methyl mercury were released into the Bay with devastating consequences and a substantial abalone kill attributed to copper pollution (Martin & Johnson, 1977). However, according to Bascom (1982) and Calabrese *et al*. (1982) extensive studies conducted on both the east and west coasts of the United States indicated that many previously accepted beliefs concerning the toxicity of metals to marine life were wrong. Another negative impact of sludge disposal into large water bodies is the excessive build-up of nitrogen and phosphorus compounds which can lead to eutrophication, characterized by increased production of a few species of algae and phytoplankton and subsequent decline in other types of species much of which cannot be consumed by predators, and therefore decomposed by bacteria reducing the available oxygen in the water column and, as the oxygen supply decreases, predatory species disappear (Riley *et al*., 1972; Bell, 1990; EMECS, 1990; Badger & Price, 1992; Odegaard *et al*., 2002).

1.4.4.2. Landfilling

Sewage sludge can be co-disposed of to landfills, in alternate layers, with municipal solid waste. In South Africa 4% of the sewage sludge produced annually is landfilled. Treatment prior to landfilling usually involves dewatering and possible anaerobic digestion (Marx *et al*., 2004) and the minimum solids concentration required is often determined by local sanitary landfill regulations. The degradation within the landfill of organic matter in sludge produces landfill gas, mostly methane. For safety reasons, this must be collected and either flared or used as an energy source. The disposal of sludge to landfills, especially that with a high water content, increases the volume of leachate that forms at the bottom of the landfill. Uncontrolled release of liquid leachate can cause severe damage to ground and surface waters (contamination by toxic heavy metals and pathogens, excess organics loading leading to de-oxygenation and eutrophication). However the addition of sludge to landfills can improve some of the chemical properties of leachate such as reducing chemical oxygen demand (COD) and raising pH from about 6.0 to 7.5 (AWWA, 1990).

Landfills may be on public land, such as a municipality owned landfill, or on private land. Although they are often located on the outskirts of cities, local residents may be subjected to unpleasant odours from sludge dumping and spreading operations (AWWA, 1990). Transport of large volumes of sludge by sealed truck or tanker from the STWs to the landfill is costly and energy intensive and it also poses the risk of accidental spillage. In addition, landfilling of sludge has become expensive because of the high costs associated with burial in properly constructed landfills. Landfilling also concentrates organic wastes and may result in point-source contamination for future generations to deal with. Today, the legislation of countries such as Sweden forbids landfilling of sewage sludge. However the biggest challenge facing landfilling of sewage sludge is the fact that there is increasing international pressure to discontinue the disposal of sludge on landfills mainly due to the space it takes up. Even in a big country such as South Africa, available landfill sites are limited and it is important that all available space be utilised as efficiently as possible (Marx *et al*., 2004).

1.4.4.3. Incineration

Incineration is a high cost/high technology option and is currently only likely to be cost-effective for large cities in developed countries (Horan, 1990). Today, incineration

technologies are highly developed (U.S.EPA, 1985) with the main types of equipment being multiple hearth and fluidized bed furnaces. Nevertheless, it does not have a high level of public acceptability due to the concerns over gas emissions, and gaining consent to construct new incinerators is often difficult. The main pollution problems arise from gaseous emissions and ash disposal, the former of which can be greatly reduced by scrubbers.

In recent years attention has been focused on pesticides and polychlorinated biphenyls (PCBs) contained in sewage sludge, which have been found to be the most thermally resistant of the chlorinated hydrocarbons. According to Gorrie and Stone Ltd. (1977), "*Test results concluded that 94% reduction of PCBs is achieved at 430°C and 99.9% at 600°C with detention times in the order of 0.1sec*". With efficient gas cleaning systems and proper furnace operation, PCBs in sludge do not appear to represent a major hazard. Such a situation, however, does not appear to prevail for the most volatile of heavy metals, mercury. A study carried out by Dewling *et al*. (1980), on the fate of heavy metals in sludge incineration found that even after a water scrubbing system to remove particulates, 97.6% of the mercury in the sludge was found in the exhaust gases. For all other metals, 99% ended up in either the ash or the wash water. Therefore, incineration is in effect only a means of sludge minimisation. It is not a means of complete disposal since 30% of the dry solids remain as ash (Marx *et al*., 2004). The ash is classified as hazardous waste due to its content of heavy metals, and so incurs further expense for its disposal in landfill sites where the main concern now centers on leachate characteristics. However, results from a Department of the Environment UK report (1995) indicated that leachate from sludge ash is generally comparable with that from municipal refuse landfills and, because of its generally small volume, represents only a small potential source of pollution. Inspite of this, there are opportunities for utilizing this ash, such as for construction materials, and using sludge as a fuel in cement production, whereby the ash becomes an integral part of the product.

1.4.4.4. Disposal on agricultural land

Application of treated sludge directly to agricultural land promotes sludge decomposition with subsequent benefits to soil and crop production. Sludge application in agriculture (as fertilizer or irrigation water) has been recognized as worthwhile, both environmentally and economically. According to a report from the Commission of the European Communities

(2000), "*the use of sewage sludge on agricultural soils as fertilizer is held as the best environmental option provided it does not pose any threat to the environment or to animal and human health*". Land application provides a feasible means of managing sewage sludge, while also providing farmers with organic matter to improve soil physical conditions and supplement conventional fertilizers usually at little or no cost (Muse *et al*., 1991). Organic matter in the sludge improves the structure and the workability (tilth) of most soils. In addition, organic matter also improves water retention, permits easier root penetration, and reduces water runoff and soil erosion (Horan, 1990; Pescod, 1992).

Sludge contains many nutrients needed for plant growth including nitrogen, phosphorus, potassium, zinc, and copper. However, the amount of nutrients in sludge vary from source to source, based on treatment process, origin, types, and quantity and quality of wastewaters treated (Muse *et al*., 1991). Nitrogen (N), phosphorus (P), and potassium (K) levels in sludge are about one-fifth of those found in typical chemical fertilizers; therefore larger amounts of sludge must be added in order to achieve the same effects as that of a commercial fertilizer. As a result, sludge can be considered a high volume, low analysis fertilizer (Jimenez *et al*., 2002). Much of the nitrogen and phosphorous in sludge is in an organic form and not all readily available to plants. When applied to land, part of the organic nitrogen will be mineralized or biologically converted into ammonium (NH_4^+), nitrate ($N0^-_3$), or both to become available to plants over time. Some nitrogen in the sludge may be lost to the air during this process because of ammonia volatilization (Conway & Pretty, 1991). To reduce the amount of nitrogen lost, sludge is often injected or ploughed into the soil directly after application. Incorporation also reduces any potential for odour problems sometimes associated with land application of sludge. Most sludges are low in potassium, and this nutrient may need to be added as a supplement to the sludge (Muse *et al*., 1991). However, excess nitrogen and potassium applied as plant nutrients have a tendency to seep into groundwater, and excess phosphorous may flow into surface water supplies with eroded sediment (Fatoki *et al*., 2003). To prevent surface and groundwater pollution, sludge nitrogen should be applied in amounts that will be utilized by actively growing plants (Muse *et al*., 1991; Richards *et al*., 2004).

Because large amounts of sludge are often applied to land, there is concern about the presence of high levels of heavy metals. This group of elements includes cadmium, zinc, nickel,

copper, chromium, lead and mercury (Muse *et al.*, 1991). These components usually occur in small amounts not harmful to plants. Some heavy metals including, zinc and copper, are micronutrients that are necessary for plant growth but excessive amounts of these heavy metals, as well as nickel can however be damaging to plants, resulting in reduced yields or even plant death (Santos & Tsutiya, 1997). Heavy metals are not very mobile and tend to accumulate in surface soils. Plant uptake of heavy metals is very low and generally the only method of removal of these metals from the soil. The most effective method to reduce heavy metal uptake by plants is to maintain a pH at or above 6.5. A near-neutral pH renders heavy metals insoluble and therefore not available to be taken up by plants (Muse *et al*., 1991). According to Muse *et al*. (1991), "*laboratory experiments have demonstrated that acute toxic effects are primarily caused by the interaction of metals with animal tissue enzymes. Opinions differ as to which metals are more toxic but, there is special concern for cadmium because it has a tendency to enter the food chain where high concentrations can be harmful. Prolonged high levels of cadmium in the diet have been shown to cause kidney failure in human beings*".

The reuse of sludge in agriculture has also been limited due to the high amount of pathogenic parasitic microorganisms of a faecal origin that they contain (Rudolfs *et al*., 1950; Bernarde, 1973; Burge & Marsh, 1978; Frakenberger, 1985; Marx *et al*., 2004). The public is reluctant to accept that reuse can be beneficial, especially when associated with problems of bad odours, potential risk of bacterial, viral and parasitic diseases that can be transmitted from man-sludge-soil-crop-man and the attraction of vectors (Jimenez *et al*., 2002). This is especially true in developing countries where data on microbiological quality of sludge are almost non-existent in spite of the fact that this represents the main problem for disposal (Hays, 1977). Some types of parasites contained in raw sludge include "somatic and F^+ coliphages, faecal coliforms, *Salmonella typhi, Pseudomonas aeruginosa,* pathogenic protozoa of water *Entamoeba, Histolytica, Giardia lamblia* and *Balantidium coli,* and helminth" (Jimenez *et al*., 2002).

Therefore, the disposal of sludge to agricultural land requires that the sludge must undergo biological, chemical or heat treatment, long-term storage or any other appropriate process to kill off disease causing organisms which may be in the sludge. Addition of quicklime to dewatered sludge has become a relatively popular process for disinfection and temporary stabilization at small and medium sized plants. The reaction of quicklime with water increases

temperature and pH, which gives a disinfection action (Odegaard *et al*., 2002). The sludge is temporarily stabilized, since it may biodegrade later when pH has dropped. Land application also exposes the organisms to sunlight, soil conditions and drastic temperature changes that destroy any remaining pathogens (Muse *et al*., 1991). The high lime dosage necessary for complying with the disinfection criteria is problematic due to the high cost of lime and limitations on land application rate due to the high lime content of the sludge. The investment cost is however low and lime treated sludge has, in most cases, a granular consistency which makes the sludge easy to spread on farmland (Odegaard *et al*., 2002).

Producers applying sludge to soils where crops are grown for human consumption must follow more rigid guidelines than producers of crops not intended for the human diet. According to the South African sludge guidelines (DNH&PD, 1991; DNH&PD, 1997), permission to apply sludge to land is principally dependent on the intended sludge use, sludge type, site conditions and current soil contaminant levels. The proposed sludge application rate is limited principally by prescribed limits on the application rate of individual contaminants in the sludge, and secondly by the nitrogen (N) needs of the crops to be grown (DNH&PD, 1991; DNH&PD, 1997). The South African sludge guidelines incorporate a permitting framework which is on a level with, if not exceeding, the most sophisticated in the world (DEAT, 2000; Marx *et al*., 2004). The framework is similar to that used by the U.S. EPA, which is the one recommended by the World Health Organisation for world-wide adoption (WHO, 1989). The inorganic trace element concentration limits for South African sludges are amongst the most comprehensive in the world, addressing a total of 13 inorganic contaminants. They are also amongst the most restrictive, with relatively low limits being defined for nearly all the elements addressed. The 1991 South African guidelines (DNH & PD, 1991) have fairly conservative limits when compared with Europe, Australia and New Zealand (Smith 1996; Steyn *et al*., 1996). On average the limits specified in the South African guidelines are about ten times more restrictive than those of the US Environmental Protection Agency and in many cases the specified concentrations are even lower than natural background levels of trace elements in some soils for soils (Smith, 1996). Extensive details on these South African sludge guidelines can be viewed in DNH & PD (1991 and 1997) and in the Permissible Utilisation and Disposal of Sewage Sludge (PUDSS) guideline document (Department of Agriculture *et al*., 1997). It is a challenge to develop criteria that are not overly restrictive to beneficial use of sewage sludge and yet protect human health from

potential harm that could be caused by hundreds of toxic chemicals that may be present in municipal sewage sludge (Page *et al*., 1983, 1987; L'Hermite, 1991).

1.4.4.5. Composting

Composting is an accelerated bio-oxidation of organic matter passing through a thermophilic stage where microorganisms (mainly bacteria, fungi and actinomycetes) liberate heat, carbon dioxide and water (Dominguez *et al*., 1997). During the composting process, the heterogeneous organic material is transformed into a homogeneous and stabilized humus-like product. Advantages of co-composting as reported by Epstein (1997), based on experience in North Carolina, USA are:

- Reduced cost of sludge composting by using the solid waste as a bulking agent;
- Incorporation of diverse waste streams (sludge, septage, solid waste, yard waste, organic industrial waste);
- Lower capital costs than most alternative technologies;
- Combining the cost of sludge and solid waste disposal;
- Process flexibility through modular construction;
- Reduced volume of mass of solid waste to landfills;
- Good environmental control;
- A usable, marketable product or products can be produced;
- Compatibility with recycling.

The process does, however, have certain disadvantages including:

- A composting facility takes up more space than combustion systems;
- Labour requirements are generally high;
- Landfill space for solid waste residuals is needed;
- A product or products are produced which need to be marketed or utilised.

Composting and a related technology, vermicomposting, are discussed in detail in Chapter 3 of this thesis. However, for completeness, a brief introduction to vermicomposting is provided.

1.4.4.6. Vermicomposting

Vermicomposting is also a bio-oxidation and stabilization process of organic material that, in contrast to conventional composting, involves the joint action of earthworms and microorganisms and does not involve a thermophilic stage (Dominguez *et al*., 1997). Phillips (1988) defines vermicomposting as "*a low cost technology system for the processing and treatment of organic wastes*". As with the composting process, vermicomposting provides a great reduction in waste bulk density, although it tends to take longer. Organic wastes including vegetable wastes and sewage sludge are broken down and fragmented rapidly by earthworms resulting in the production of two useful products: earthworm biomass and the vermicompost. The latter is a finely divided peat-like material with excellent structure, porosity, aeration, drainage and moisture-holding capacity (Sabine, 1988). The earthworm biomass can either be processed into proteins (earthworm meal), or high-grade horticultural compost (Hand, 1988; Phillips, 1988; Sabine, 1978 and 1988).

The application of composting and vermicomposting processes to waste management has primarily sought to obtain products which are commercially valuable. For this reason, many of the other possibilities they offer have been disregarded and left unstudied. Dominguez *et al*. (1997), consider it to be of utmost importance to apply one of these two processes in order to stabilize organic wastes, at the same time managing to solve, or at least minimize, the environmental problems arising from their disposal.

The discussion of sludge treatment and disposal technologies indicates that there is no single treatment and disposal option which does not pose some threat to the environment and/or human health. Therefore, it may be desirable to investigate an integrated waste management system approach in order to determine whether a combination of treatment processes may be able to provide a safe, sustainable disposal of sewage whilst at the same time addressing some of the constraints to waste management initiatives in developing countries. Section 1.5 provides an introduction to integrated waste management systems.

1.5. INTEGRATED WASTE MANAGEMENT SYSTEMS

Past decisions on waste management strategies and the structure of waste management systems relied either explicitly, or implicitly, on the 'waste management hierarchy' (DEAT,

2000). This varied in its exact form, but usually gave the following order of preference; waste reduction, re-use, materials recycling, composting, incineration with energy recovery, incineration without energy recovery and finally landfilling (White, 1995 and 1997). The 'waste hierarchy' ranks individual waste management options in a priority order, but cannot deal with two or more options integrated together. According to McDougall (2000), such use of a priority list for the various waste management options has serious limitations, which include:

- The hierarchy has little scientific or technical basis. There is no scientific reason why materials recycling should always be preferred to energy recovery;
- The hierarchy is of little use when a combination of options is used, as in an integrated waste management system. In an integrated waste management system, the hierarchy cannot predict for example, whether composting combined with incineration of the residues would be preferable to materials recycling plus landfilling of residues. What is needed is an overall assessment of the whole system, which the hierarchy cannot provide;
- The hierarchy does not address costs. Therefore it cannot help assess the economic affordability of waste systems.

Although useful as a mental checklist, the waste hierarchy will not always indicate the most sustainable waste management option for particular waste streams (Department of Environment United Kingdom, 1995). In line with the three pillars of sustainable development, waste management needs to be environmentally effective, economically affordable and socially acceptable. Environmental effectiveness requires that the overall environmental burdens of managing waste are reduced, both in terms of consumption of resources (including energy) and the production of emissions to air, water and land. Economic affordability requires that the costs of waste management systems are acceptable to all sectors of the community served, including householders, commerce, industry, institutions and government. Finally, social acceptability requires that the waste management system meets the needs of the local community, and reflects the value and priorities of that society (White *et al*., 1995). Along with the overall need for sustainable waste management, it is also becoming increasingly clear that no single treatment method can manage all material in municipal solid waste in an environmentally effective way (White & McDougall, 1998).

In integrated waste management, decisions on waste management take account of different waste streams, collection, treatment and disposal methods to achieve a balance between collection and treatment methods that strive for environmental sustainability, cost effectiveness and social acceptability (Thurgood, 1998; Wilson, 1998). Following a suitable collection system, a range of treatment options will be required, including materials recovery, biological treatment (composting and/or biogasification), thermal treatment (burning of refuse derived fuel), packaging derived fuel and/or mass-burn incineration and landfilling (White, 1997). Such an approach is advocated in the current United Kingdom waste strategy, 'Making Waste Work' which states that "…*it is likely that an integrated approach, where each option contributes to the overall recovery of the waste, will usually be the preferred practice."*

Although limited by technical and financial resources, developing countries have the potential to significantly improve management of sewage sludge and it is clear from the discussion above that the best path to take in order to make sludge management efficient and effective in these countries is one that follows and implements certain elements of integrated waste management. Instead of focusing primarily on attempting to make single treatment and disposal options work better, the focus should be shifted to using a combination of these methods so as to gain a management system that is environmentally, economically and socially acceptable. The scale and nature of integrated waste management systems varies considerably, and included within the broader definition would be the highly integrated waste beneficiation systems based on the ecological engineering approach (Todd *et al*., 2003). Such systems employ a variety of inter-linked waste conversion steps to derive value from agricultural waste. Such an approach should be investigated for disposal of sewage sludge, especially at smaller STWs in developing countries.

Although the scope of the problem with regards to sludge management of the STWs is endemic or generic to most provinces in S.A, the focus of the research is the Eastern Cape. Research conducted by Antrobus (2003) and Mohale (2003) showed that STWs in the Eastern Cape Province of South Africa were overloaded and were discharging 'treated effluent' of a quality that did not meet standard limits as outlined in the legislation. Based on these findings, it was considered important to also examine the sludge management of STWs within the Province. This research therefore aimed to assess the need for appropriate sludge management technologies within the Eastern Cape Province of South Africa, and to design and test the

feasibility of one such integrated system for the management of sewage sludge. The objective of designing this integrated waste beneficiation facility (IWBF) was to overcome at least some of the constraints to waste management discussed in Section 1.2 of this thesis. Of particular importance was the need to design a system that improved the economic sustainability of treatment operations while making use of appropriate and existing skill levels. Section 1.6 below outlines the hypothesis, objectives and key questions of the current research.

1.6. RESEARCH HYPOTHESIS, PROJECT OBJECTIVES, KEY QUESTIONS

1.6.1. Research Hypothesis

The current management of sewage sludge generated during the treatment of municipal wastewater in the Eastern Cape Province of South Africa is poor and, as such, this material poses a threat to the local environment. The development of an IWBF, incorporating appropriate technologies, can provide an environmentally, socially, economically and technically sustainable solution to the above problem in the Province and in other developing countries.

1.6.2. Project Objectives

The objectives of the current project were to:

1) Investigate the magnitude of sludge production in the Eastern Cape and identify potential environmental threats associated with current disposal methods;
2) Through a rational approach, design an appropriate conceptual IWBF that would enable safe disposal of sewage sludge while at the same time providing non-legislative incentives to improve sludge management;
3) Assess the sustainability of the conceptual IWBF in terms of its environmental, social, economic and technical implications, within the context of a developing country.

1.6.3. Key Questions

1) What is the current status of sewage sludge management within the Eastern Cape with regards to volumes and disposal routes?

2) Do current sludge disposal practices pose any threat to the environment?
3) Would an IWBF consisting of various sewage and sludge treatment technologies provide a suitable and sustainable alternative to existing sludge management practices in the Eastern Cape Province of South Africa?
4) What are the potential barriers to the sustainability (technical, social, environmental and economic) of the proposed IWBF?

CHAPTER 2

SLUDGE MANAGEMENT BY WASTEWATER TREATMENT WORKS IN THE EASTERN CAPE: THE STATUS QUO

2.1. INTRODUCTION

The Eastern Cape is economically South Africa's poorest province, with a consistently higher unemployment level than the national average and a relatively large rural population (Woolard, 2002). According to a United Nations Development Program (2001) provincial profile "*…out of all South Africans that fell within the non-economically active group, 18% were from the Eastern Cape, which is a higher proportion than its (percentage of the national) population*" and according to statistics compiled in the last quarter of 2002, the official unemployment rate in the Province was 32.5% - an estimated 594,000 people were not economically active (IRIN, 2004).

The apartheid system left the Eastern Cape community with a lack of services such as health, education, housing and sanitation and demographic surveys in the State of South Africa Population Report (2000) showed that approximately 50% and 66% of households in the Eastern Cape did not have access to treated water and sewage treatment facilities, respectively. There were only 196 STWs listed in the Eastern Cape Province (Mohale, 2003) and Morrison *et al*. (2001) found that although most facilities were already exceeding their capacities, no expansion or upgrading had occurred. Although the Reconstruction and Development Program (RDP) approved 1025 water and sanitation facilities to be constructed in the Eastern Cape, only 195 were constructed (RDSN, 2003). This means that majority of RDP housing units are still reliant on existing STWs.

Mohale (2003) evaluated the efficiency of 98 of the 196 STWs in the Eastern Cape Province which had been monitored by the Department of Water Affairs and Forestry (DWAF) between January 2002 and May 2003 by examining the quality of 'treated' effluent they discharged and drew the following conclusions:

- Only 12% of the STWs included in her study regularly produced effluent that met discharge requirements set out by the National Water Act 36 of 1998 of South Africa;

- The main parameters of concern included ammonia, phosphate, nitrate/nitrite and biological oxygen demand (BOD);
- Approximately 41% and 46% of all STWs surveyed disposed of their final effluent by using it for irrigation or discharging it into rivers respectively.

Following Mohale's (2003) conclusions, it is not surprising that effluent discharges from STWs in the Eastern Cape Province were found to be the major polluters of rivers such as Umtata, Keiskamma and Isinuka (Faniran *et al*., 2001; Morrison *et al*., 2001; Fatoki *et al*., 2003). Rural communities in these areas are still reliant on the contaminated waters of these rivers for drinking, recreation, irrigation, fishing and livestock watering purposes (Faniran *et al*., 2001; Fatoki *et al*., 2003; Mohale, 2003). Fatoki *et al*. (2003) found that a lack of access to clean water and sanitation facilities results in outbreaks of water borne diseases such as cholera. There have indeed been reports of cholera epidemics in the Eastern Cape that are thought to have been caused by high discharges of sewage which did not meet required standards (RDSN, 2003). The first cholera case in the Eastern Cape was reported in February 2001 in Qingqolo in the former Transkei area. This cholera epidemic spread to the Hlabatshane area in Mqanduli in February 2002, where it preceded to infect 267 people and resulted in 11 fatalities (Fatoki *et al*., 2003).

From the introduction above it is clear that poor effluent treatment by STWs in the Eastern Cape Province poses a significant threat to human health and the environment. However, unlike effluent treatment, very little is known about the other product of wastewater treatment, sewage sludge. The management of this potentially hazardous material will be particularly important if Millennium Development Goals related to sanitation provision are to be met at least partially through conventional waterborne sewage treatment technologies. Additionally since the broader impacts of current sludge management practices in the Eastern Cape are unknown, they provide an incentive for improved management of this hazardous material and for the development of alternative disposal routes. As a result, the main objective of this initial aspect of the study was to determine if current sludge management by STWs in the Eastern Cape Province of South Africa posed any environmental, economic or social risks and if so, the magnitude and nature of these risks. This objective was achieved by seeking answers to the following questions:

- Which facilities were responsible for the production of sewage sludge in the Eastern Cape?
- What quantity of sewage sludge was generated at these facilities?
- What was the quality of sewage sludge (pathogen and heavy metal levels) generated at these facilities?
- What was the current fate of sewage sludge produced in the Province?
- What were the environmental, economic, and social implications of current sewage sludge management?
- Was there a difference in sludge management by facilities in metropolitan areas and small towns within the Province?

2.2 METHODS AND MATERIALS

2.2.1. Sludge production in the Eastern Cape Province

Determining sludge production in the Eastern Cape Province firstly involved identifying all the facilities producing sludge in the Province and, secondly, ascertaining the quantities of sludge produced by each of these facilities.

2.2.1.1. Sludge treatment facilities currently available in the Eastern Cape

A list of sewage treatment facilities currently operating in the Eastern Cape and treatment technologies employed compiled by Mohale (2003) based on information obtained from DWAF was used as a starting point. This Information was cross-checked with DWAF and other municipal officials and any additional data included. Once the facilities had been identified, the quantities of sludge produced by each of them could then be ascertained.

2.2.1.2. The quantity of sludge generated by the Eastern Cape's STWs

In most cases, the volume of sludge generated at the Eastern Cape's STWs on a daily, monthly or even annual basis was not available since sludge volumes were neither monitored nor recorded. However, the current study managed to obtain records of the amount of sludge produced at three of nine sample STWs in the Province selected for in-depth studies (section 2.2.2) namely: Fish Water Flats, Cape Receife and Driftsands. A method developed by Marx *et al*. (2004) for the Water Research Commission of South Africa was then adopted.

Marx *et al*. (2004) estimated the daily production of sludge in South Africa based on the assumption that all wastewater treatment works with a capacity of less than 1.0 ML/day were oxidation ponds which did not produce sludge. In addition, no differentiation was made between treatment processes. These assumptions were adopted for the current study. Marx *et al*. (2004) found that for every ML of wastewater treated daily, 150 kg (dry solids) primary sludge and 200 kg (dry solids) waste activated sludge were produced. The quantity of sludge could be reduced by 30% and 15% through digestion of primary and waste activated sludge respectively. The validity of this method was tested using sludge production data from the three above mentioned STWs.

Table 2.1 below indicates the actual sludge volumes, as obtained from the managers of the three sample STWs in the Eastern Cape that had kept some records, and the predicted sludge volumes of the same STWs as calculated using the method proposed by Marx *et al*. (2004). A two sample T-test assuming unequal variances was conducted to determine whether predicted and actual sludge volumes were significantly different. The results of the T-test revealed no significant differences ($p>0.05$) between predicted and actual sludge volumes and, as a result the current study could safely use the Marx *et al*. (2004) method to calculate sludge volumes for STWs in the Eastern Cape Province.

Table 2.1: Predicted and actual sludge volumes of three sample STWs in the Eastern Cape.

Name of STW	**Actual sludge volumes as obtained from STW managers (tDS/day)**	**Predicted sludge volumes using Marx *et al*. (2004) method (tDS/day)**
Driftsands	2.7	2.63
Fish Water Flats	38	39.2
Cape Receife	4	4.2

2.2.2. Impact assessment of sludge management at the Eastern Cape's STWs

Conducting an impact assessment of sludge management at the Eastern Cape's STWs first entailed selecting representative sample STWs where in-depth studies on sludge quality, current sludge management practices (treatment and disposal), and possible economic,

environmental and social impacts of management practices could be conducted. Provided below are details on each of the STWs selected by the current study and the reasons as to why they were selected.

2.2.2.1. Sample sewage treatment works

Nine STWs in the Eastern Cape Province were selected for in-depth studies. Six of these were located in the Nelson Mandela Metropolitan Municipality (NMMM), one in Makana Municipality, one in Camdeboo Local Municipality and the other in the Inxuba Yethemba Local Municipality. These municipalities were selected because they provided a good basis for comparison especially when determining the differences, if any, in sludge management by STWs located in large metropolitan cities and small towns. NMMM is a large metropolitan area (population 1 005 776 in October 2001) and covers the areas of: Port Elizabeth, Uitenhage, Despatch, Blue Horizon Bay, Western District Council, and Seaview, whereas Makana, Camdeboo and Inxuba Yethemba municipalities all cover small towns. Makana is a local municipality (population 74 526 in October 2001) and encompasses Grahamstown, Alicedale and Riebeek East. Camdeboo local municipality (population 44 367 in October 2001) covers the towns of Aberdeen, Nieu-Bethesda and Graaff Reinet. Inxuba Yethemba (population 60, 306 in October 2001) serves the towns of Cradock and Middleburg.

Figure 2.1 shows the location of the towns in the Eastern Cape Province in which the nine sample STWs were located and Table 2.2 provides a detailed description of each of the sample STWs in terms of their actual locations, design capacity and the treatment technologies employed.

The methods used to ascertain sludge quality, current sludge management practices, and the economic, environmental and social implications of these practices follow.

2.2.2.2. The current fate of sewage sludge in the Eastern Cape Province

Determining the current fate of sewage sludge in the Eastern Cape Province involved conducting site visits in August 2004 to each of the nine selected sample STWs and then observing and recording their sludge treatment and disposal practices. Observations were confirmed via interviews with STW managers.

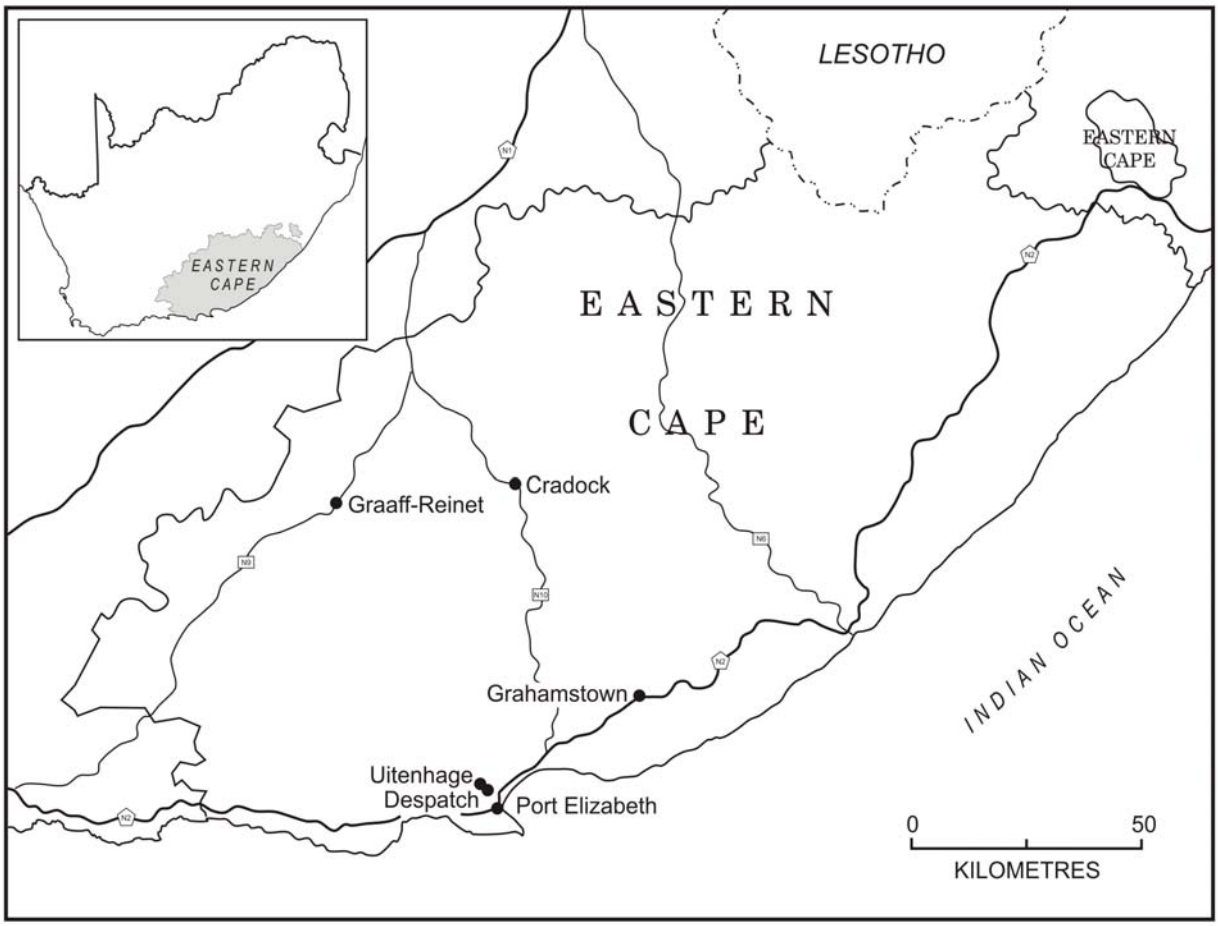

Figure 2.1: The location of the towns in the Eastern Cape in which the nine sample STWs investigated in the current study were located.

2.2.2.3. The quality of sludge generated at the Eastern Cape's STWs

None of the sample STWs conducted any analyses regarding the quality of sludge generated. However, data on the main components of sludge that were a cause for concern (i.e. heavy metals and pathogens) was fundamental to determining the risk posed by current sludge management practices in the Province. In addition, the results of these analyses would provide some indication of the potential uses of this material as well as the effectiveness of sludge treatment at each of the STWs.

Sewage sludge samples were collected from each of the nine sample STWs in August 2004. The fresh sludge samples were collected from sites where sludge was stored immediately after treatment but before disposal (e.g. drying beds). Approximately 200g of sludge was collected at each of the STWs. All glassware used to store collected sludge had been washed in 5%

Table 2.2: Description of each of the nine sample STWs selected for in-depth studies in the current research.

Municipality	Name of STW	Location of STW	Design capacity (ML/day)	Technology type
NMMM	Fish Water Flats	Blue Water Bay (Port Elizabeth)	112	Activated sludge
	Driftsands	Close to Port Elizabeth airport in the Madiba Bay project area (Port Elizabeth)	7.5	Activated sludge
	Cape Receife	Cape Receife Nature Reserve (Port Elizabeth)	12	Activated sludge
	Kelvin Jones	Opposite Volkswagen head offices (Uitenhage)	22	Activated sludge
	Kwanobuhle	Outskirts of Uitenhage	7.8	Activated sludge
	Despatch	Outskirts of Despatch town	4.6	Activated sludge
Makana	Belmont River Valley	South-East side of Grahamstown in the Belmont valley	5.14	Biological filtration system
Camdeboo	Graaff Reinet	Corner of national road to Port Elizabeth and N9 to Aberdeen	3	Activated sludge and trickle filter
InxubaYethemba	Cradock	Swaershoek Road	4.8	Activated sludge

nitric acid and soaked for at least four hours in order to remove adsorbed metal residues and had been soaked for a further hour in distilled water. As soon after collection as possible, samples were analysed for heavy metal and pathogen content as described below.

a) Heavy metal analysis

Sludge samples brought back to the laboratory were dried in an oven at 30^{o}C until a constant weight was reached. After drying, the Toxicity Characteristic Leaching Procedure (TCLP) method was used to prepare the samples. The TCLP was developed in the USA by the Environmental Protection Agency to measure a waste's leachability and hence the risk it poses to ground water (US EPA, 1995). Dry sludge samples were mixed with a known volume of TCLP solution (1gram of sludge = 20ml of TCLP solution). The TCLP solution used had a pH of 2.88 and contained 5.7 ml 100% glacial acetic acid mixed to a volume of 1 litre using double distilled water. A sample of sludge was then extracted over a period of 20 hours. Samples with a pH greater than 2.0 were acidified by adding concentrated nitric acid, while stirring with a submerged pH probe sensor. After completion of the TCLP, samples were filtered through a 0.45 um cellulose acetate membrane and the filtrate stored at 5^{o}C temperature (stops the water evaporating off and concentrating the metals), until analysis was conducted by atomic absorption spectrometry (AA specs) as per the manufacturer's instructions (Perkin-Elmer). Extensive details on the TCLP can be viewed in the Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste document (DWAF, 1998).

Each sludge sample was tested for concentrations of the following metals: cadmium, zinc, copper, nickel, lead and mercury. These were selected because, as previously stated (Chapter 1, Section 1.4.4.1), they appear to pose the biggest concern to environmental and human health resulting from their accumulation especially in soil and the food chain. In addition, these are the metals whose levels are specified in the guidelines for sludge use (Department of Agriculture *et al*., 1997). Although the metal analysis was also intended to determine the levels of chromium in the samples, due to difficulty in obtaining the correct chromium standards, this could not be achieved.

b) Pathogen analysis

The pathogens most commonly present in sewage sludge are bacteria (*Salmonellae spp*.), parasites (*Ascaris lumbricoides*) and faecal coliforms. Due to the potentially hazardous nature of the pathogens within the sludge, all sludge samples were sent to an external accredited laboratory for pathogen analysis. Standard methods were employed to test for the presence of

Ascaris ova, *Salmonella spp, Shigella, Vibrio cholera* and *E.coli*. The accredited laboratory used xylose-fermentation, lysine decarboxylation and the production of hydrogen sulphide for primary differentiation of *Shigellae* and *Salmonellae* from non-pathogenic bacteria. *Salmonella* species were differentiated from non-pathogenic xylose fermenters by the incorporation of lysine in the medium. *Salmonella* take up the xylose and decarboxylate the lysine, thus altering the pH to alkaline and mimicking the *Shigella* reaction. The presence of *Salmonella* species was differentiated from that of *Shigella* by a hydrogen sulphide indicator. Rapid xylose fermentation is almost universal amongst enteric bacteria, except for members of the *Shigella* genera. Xylose was thus included in the medium so the *Shigella* species could be identified by a negative reaction. Thiosulphate-citrate-bile-sucrose agar (TCBS) is a highly selective agar for the isolation of *Vibrio chlorae* as well as other vibrios, and was used in order to detect *V.chloreae* which produces large yellow colonies if present. Analysis of *E.Coli* was conducted using the membrane filtration technique in which samples were filtered through cellulose membranes having a pore size of 0.45um. These retained all the bacteria on their surface and the membrane was then placed on a nutrient medium (broth or agar) and incubated for a given time at a given temperature. Bacteria of the species or group favoured by the particular medium grew into visible colonies on the membrane and took on a particular colour depending on the stains contained in the medium. They were then counted directly (APHA, 1989)".

2.2.2.4. The environmental, economic and social implications of current sludge management practices by Eastern Cape STWs

Chapter 1 of this thesis indicated that current sludge management practices posed a threat to human health and the environment due to undesirable contaminants contained in sludge. One way to determine possible threats was by means of an environmental risk assessment. A risk assessment is the quantitative or qualitative evaluation of the potential for impacts resulting from a particular action occurring (in this case sludge disposal) and the magnitude of the consequences that result from that action (US EPA, 1995). The main objectives of risk assessment are to assist in understanding where environmental risks arise from a particular action, to assess the significance of these risks and ultimately to enable management of these risks. The objectives outlined for this research clearly highlighted the need for identification and assessment of the environmental risks associated with sludge disposal. The parameters

used for risk assessment in the current study included; probability, duration, spatial scale, certainty, and severity. Each of these parameters is discussed in further detail below.

The parameters were also associated with a scoring system which attached numerical values to each parameter so as to aid in calculating and assigning an overall risk as a result of current sludge disposal practices for each of the nine sample STWs. In most cases, the numerical values ranged from 0-4 depending on the parameter that was being assessed. However, some parameters such as spatial scale had values that ranged from 0-6. Higher values (4) were attached to those factors within each parameter that posed the greatest risk or had the greatest reach and lower values (0) attached to those that posed the least risk or had the least reach. Overall risk was calculated by obtaining the sum of the numerical values that had been attached to each parameter.

Provided below are the details on each of the parameters and attached to each are the associated scoring systems that were discussed above.

1) Probability: How often is a particular impact likely to occur?

0-*Improbable:* The chance of these impacts occurring is of a low likelihood. Such impacts are likely to occur less than once a month but more than once a year.

1-*Probable*: Such impacts are likely to occur highly less than once a week but more than once a month.

2-*Highly probable*: Such impacts are likely to occur less than once a day but more than once a week.

3-*Definite*: These impacts are likely to occur on a continuous basis or at least once a day, regardless of mitigation measures.

2) Duration: For how long will the impacts last?

1-*Short term*: Less than 5 years

2-*Medium term*: 5-20 years

3-*Long term*: 20-40 years, and from a human perspective, essentially permanent. However, these impacts will cease after the operation ends

4-*Permanent*: Over 40 years, and resulting in a permanent and lasting change that will persist indefinitely.

3) Spatial extent: Over what area will the impact occur?

0-*On site:* Occurs only within the boundaries of the sludge disposal/

1-*Immediate Surrounding area*: The impact could affect the people living within 500m from the boundaries of the sludge disposal/

2-*Town/City*: The impact could affect the residents of the town/city, in which the STW is situated

3-*Municipal*: The impact could affect the people in the local municipality

4-*District*: The impact could affect the people living in the administrative district municipality

5-*Regional*: The impact could affect the people living in the Province

6-*National*: The impact could affect the people in the country.

4) Certainty: How certain the researchers are in their predictions?

1-*Unsure*: Less than 40% sure of a particular fact or of the likelihood of the impact occurring.

2-*Possible*: Only over 40% sure of a particular fact or of the likelihood of the impact occurring.

3-*Probable*: Over 70% sure of a particular fact, or of the likelihood of the impact occurring.

4-*Definite*: More than 90% sure of a particular fact. To use this, one needs to have substantial supportive data.

5) Severity: How severe is the impact? Severity will also depend to some extent on how much the impact infringes upon specific legislation and permit requirements. However, compliance with legislation will be addressed as a separate issue.

1-*Slight*: Mitigation of impacts on the affected system or party is very easy, cheap, not time consuming or is not necessary. These impacts are easily reversible.

2-*Moderately severe*: Impacts on the affected system or party that can be mitigated. These impacts are reversible.

3-*Severe*: Impacts to the affected system or party that can be mitigated. However, this mitigation would be difficult, expensive or time consuming or some combination of these. In addition, these impacts are not easy to reverse.

4-*Very severe*: An irreversible and permanent change to the affected system or party which cannot be mitigated.

2.3. RESULTS AND DISCUSSION

2.3.1. Sludge production in the Eastern Cape Province

2.3.1.1. Sludge treatment facilities currently available in the Eastern Cape

There are currently 196 STWs in the Eastern Cape Province. Of these, 52 (approximately 27%) employ technologies that produce and treat sewage sludge (Mohale, 2003). Appendix I shows the sewage treatment technologies employed at all 52 sewage treatment facilities that produce and treat sludge in the Eastern Cape Province.

2.3.1.2. The quantity of sludge generated by the Eastern Cape's STWs

The predicted mass of sludge generated by the 52 STWs in the Eastern Cape Province can be viewed in Appendix I and in Figure 2.2 below.

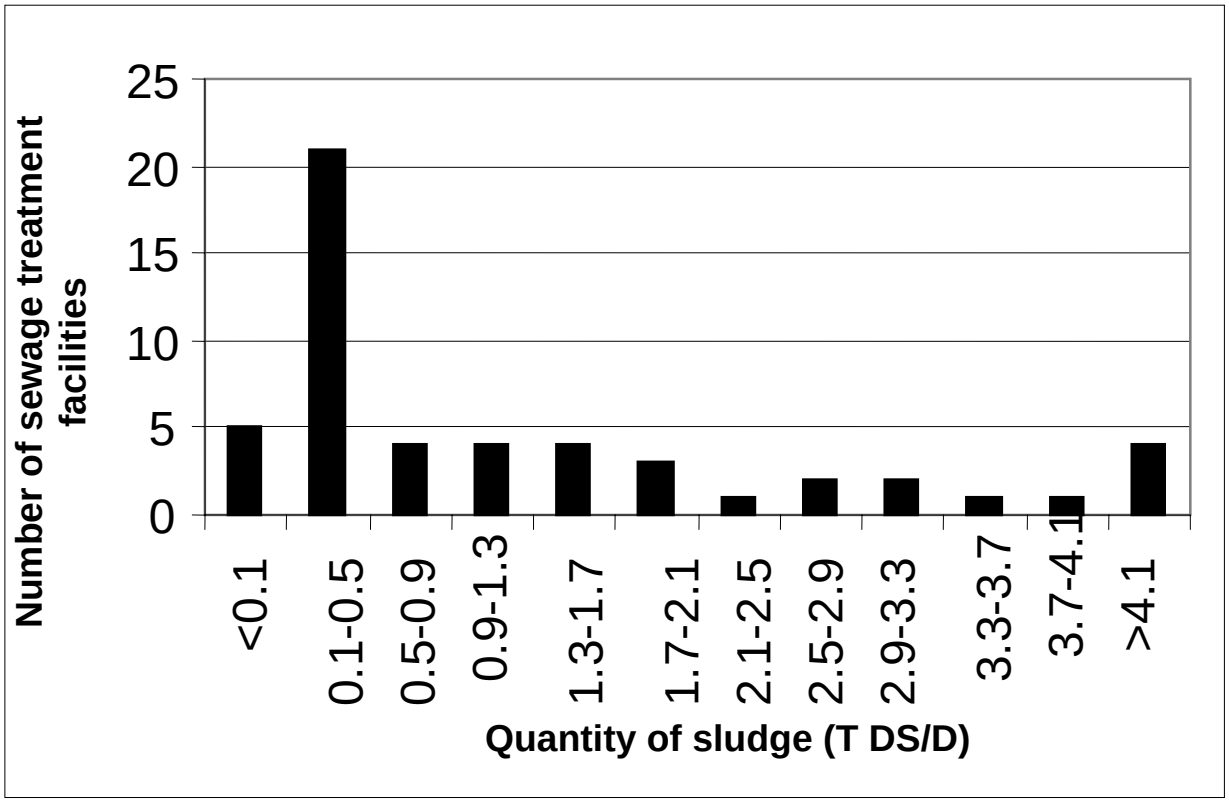

Figure 2.2: The quantity of sludge currently generated by sewage treatment facilities in the Eastern Cape Province daily (tons dry solid per day).

It is clear from Figure 2.2 that 22 of the 52 STWs (approximately 42%) generated between 0.1-0.5 tDS/day each. Only five STWs (approx. 9.6%) produced 4.1tDS/day and more. By making use of the formula (Marx *et al*., 2004), the Eastern Cape Province was found to generate an estimated 116 tDS/day and it was not surprising that the STWs predicted to generate the largest quantities of sludge were the ones that possessed the largest capacities and were located in large metropolitan cities. In descending order these were: Fish Water Flats (Port Elizabeth), East Bank reclamation works (East London), Kelvin Jones (Uitenhage), Queenstown, Cape Receife (Port Elizabeth), Umtata, Mdantsane, Potsdam, Zwelitsha, Kwanobuhle (Uitenhage) and Driftsands (Port Elizabeth). These 11 STWs accounted for approximately 21% of all the sludge producing facilities available in the Province however they contributed 77% of the total daily sludge production in the Eastern Cape. The amount of sludge produced outside the major cities was relatively small and was estimated at approximately 23% of total daily sludge production in the Province.

Marx *et al*. (2004) calculated that the whole of South Africa, which has 900 STWs, generates an estimated 3125 tDS/day. Based on these figures, the Eastern Cape has 22% of all the STWs in the country of which only 27% contribute 3.7% to the total amount of sludge produced in South Africa daily. This low percentage contributed by the Eastern Cape to sewage sludge production in South Africa could be attributed to the fact that relative to its population there are still relatively few sewage treatment facilities available in the Province and furthermore most of the technologies employed for sewage treatment in the Province (approx 73%) are low cost technologies such as oxidation ponds that do not regularly produce sewage sludge for disposal (Mohale, 2003).

The current study found that although Marx *et al*. (2004) assumed that all STWs with a capacity of less than 1.0 ML/day were oxidation ponds and therefore did not produce sludge, this particular assumption did not hold true since some of the STWs in the Eastern Cape Province with a capacity of less than 1.0 ML/day were not oxidation ponds but instead employed technologies that actually produce sludge. These STWs included Da Gama, MiddleDrift, Peddie, Mpekweni Sun, Nahoon, Seymour STW, Sterkstroom, Grootfontein agricultural college STW, Kirkwood, Kirkwood correctional STW and Mazamba village market (Appendix I). This invalid assumption means that total daily sludge production volumes calculated for South Africa were underestimated since at least eleven of the Eastern

Cape's STWs were not used by Marx *et al*. (2004) in their calculations. This might also have been the situation in South Africa's other eight Provinces, and should be subject to further investigation.

It is also important to note that in the current research, calculations were carried out based on the design capacity of each of the STWs, and as a result some of the sludge volumes calculated for STWs may be higher or lower than actual production quantities. As suggested by Mohale (2003), some STWs may be receiving more wastewater than specified by their design capacity, therefore producing more sludge, whereas others particularly those that have been recently upgraded may be currently receiving less water than they are designed to handle therefore producing less sludge. This potential limitation needs to be addressed more thoroughly in future studies.

2.3.2. Impact assessment of sludge management by the Eastern Cape STWs

2.3.2.1. The current fate of sewage sludge in the Eastern Cape Province

The nine sample STWs processed and disposed of their sludge in a number of ways (Table 2.3). Figure 2.3 is an extension of Table 2.3 and indicates the sludge disposal sites of four of the nine sample STWs.

It is clear from Table 2.3 that of the nine STWs studied, six disposed of their sludge in stockpiles on open plots of land, one disposed of sludge to a landfill site and two used their sludge in brick making and as fertiliser on land. It was evident that these sludge disposal methods presently employed by the nine sample STWs did not conform to environmental requirements although the exact risk posed by each STWs was likely to vary. This is because, a final decision on how these disposal techniques affect the environment could only be reached once the quality of the sludge being disposed of was ascertained and a risk assessment conducted for each of the STWs. Therefore, the possible environmental, social and economic implications of these current sludge disposal techniques will only be discussed in detail later on in this chapter under the section on implications of current sludge management techniques however, provided below are the results of the sludge quality analyses.

Table 2.3: Current methods of sludge disposal by nine sample STWs in the Eastern Cape.

Name of STW	Sludge processing step	Current sludge disposal technique
Belmont River Valley	Drying beds	Dry sludge is disposed of on an embankment 50m from the Bloukrans river
Fish Water Flats	Heat conditioning	Dry sludge is transported via road to Coega Brick where the sludge is used in brick making
Driftsands	Drying beds	Dry sludge is dumped on sand dunes
Cape Receife	Drying beds	Dry sludge is dumped on sand dunes in the Cape Receife nature reserve
Kwanobuhle	None	Liquid sludge is transported via pipeline to an open plot of land adjacent to the STW
Kelvin Jones	None	Liquid sludge is transported 7 km via pipeline off the site of the STW to a landfill site
Despatch	Drying beds	Dry sludge is dumped on an open plot of land adjacent to the treatment works
Graaff Reinet	Drying beds	Dry sludge is either dumped on an open plot of land near the treatment works or used on sports fields as fertiliser
Cradock	Drying beds	Dry and sometimes wet sludge is dumped at the local solid waste disposal site

2.3.2.2. The quality of sludge generated at the Eastern Cape's STWs

a) Heavy metal concentrations

The heavy metal concentrations of sludge from the nine sample STWs were compared to the maximum allowable metal and inorganic content in mg/kg dry sludge as published in the Permissible Utilisation and Disposal of Sewage Sludge document (PUDSS) (Department of Agriculture *et al*., 1997). Although these allowable concentrations were sub-divided into two fractions, the leachable fraction of inorganic substances which addressed DWAF's concerns and the total inorganic substances which addressed the concerns of the Departments of Health and Agriculture, this study only compared heavy metal concentrations present in each sludge

Sludge disposal site	Name of STWs, and factors to note
	**Belmont River Valley** Sludge disposal site Bloukrans River
	**Despatch** Sludge disposal on open plot of land next to STWs Residential area
	**Kwanobuhle** Close proximity of community to STW that disposes of sludge on site
	**Kelvin Jones** Landfill site to where liquid sludge is transported 7km via pipeline from the STWs

Figure 2.3: Sludge disposal sites of four of the nine sample STWs researched in the current study.

sample to the leachable fraction of inorganic substances (Table 2.4).

Table 2.4 shows that based on a once-off survey, sludge at all the sample STWs except for Driftsands met the requirements set out in the guideline document PUDSS (Department of Agriculture *et al*., 1997) with regards to the levels of all six heavy metals. Sludge from Driftsands met all the requirements for all the metals except mercury, and the levels of this metal were five times that of recommended levels. This implied that Driftsands may have been treating wastewater that contained either mercury and/or related compounds. According

Table 2.4: Heavy metal levels present in the treated sludge of nine sample STWs in the Eastern Cape compared to the leacheable fraction allowed by PUDSS. All values in mg/kg dry sludge

Metal	**Leachable fraction allowed**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Cadmium	15.7	0	0	0.1	0	0.1	0	0	0.3	0.2
Zinc	353.3	10.2	29.3	73.9	38.8	100	7	2.93	5.8	10.1
Copper	50.5	0	0.9	0	0	2.8	1.3	0	0.9	0.1
Nickel	200	3.8	1.8	5.2	15	2.3	0	0	0.4	0.5
Lead	50.5	0	1.2	0.5	0.6	22.6	0.1	0.3	0.6	0.7
Mercury	10	4.3	0	0	3.2	**53**	0	2.02	3	2.9

KEY:

A= Kelvin Jones, **B**=Despatch, **C**=Fish Water Flats, **D**=Cape Receife, **E**=Driftsands, **F**=Kwanobuhle, **G**= Belmont River Valley, **H**= Cradock, **I**=Graff Reinet

to PUDSS (Department of Agriculture *et al*., 1997), the following industries produce mercury and/or related compounds: bioside manufacture (mercuric acid), rubber and plastic materials (mercuric chloride and mercury oxide), pharmaceuticals and cosmetics (mercurous chloride) and electronic and electrical engineering (mercury metal). These results have important implications for Driftsands' sludge because if it were to be earmarked for recycling, the source of the input would need to be located and input to the sewer of mercury containing

effluent would need to be stopped. Interestingly, Fish Water Flats STW also treats industrial, pharmaceutical and cosmetic wastes but the levels of all heavy metals including mercury fell within recommended values. A possible explanation is that industries located within the catchment of Fish Waster Flats STW have employed on-site treatment to remove potentially toxic compounds, including mercury, prior to release of wastewater to the sewer, while at least one facility within the catchment of Driftsands was not.

Although the sludge collected from the other eight STWs exhibited heavy metal concentrations within acceptable limits (Department of Agriculture *et al*., 1997), heavy metals tend to accumulate in the soil particularly when large volumes of sludge are disposed of over an extended period of time. The residence time of heavy metals is very long and although they accumulate in the soil, they tend to be immobilised and are often unavailable for uptake (Muse *et al*., 1991; Woodyard, 2001). However, according to Horan (1990), although these heavy metals adsorb to the sludge, it is possible that partially stabilised sludge could undergo anaerobic digestion. This would result in the production of fatty acids which could reduce the pH of the sludge and under these conditions; some of the immobilised metals may become soluble and leach from the sludge during periods of rainfall. As a result, the heavy metal content of sludge will always vary depending on the degree of stabilisation, temperature and rainfall. It is therefore possible that although "fresh" sludge was used for analysis of heavy metals, that the variation may be explained to some extent by local climatic conditions and sludge processing.

b) Pathogen concentrations

No viable pathogens or ova were detected in any of the sludge samples collected from the nine sample STWs in the Eastern Cape Province of South Africa. It was not surprising that no pathogens were present in the sewage sludge from Fish Water Flats STWs since their sludge treatment technology (heat conditioning) entails the use of high temperatures (170^0C-200^0C) for a period of 20-30 minutes (depending on the sludge characteristics) specifically to kill any pathogens. Natural ultraviolet radiation could also have contributed to the absence of pathogens in the sludge samples of the other eight sample STWs, since the sludge samples used in pathogen analysis were collected from sites which had all been exposed to ultraviolet radiation. According to a series of experiments conducted by Epstein *et al*. (1998), *E.Coli* in

sludge decayed to background levels within 96 days mainly because predatory microorganisms and ultraviolet radiation worked against the survival of pathogens in sludge. While every attempt was made to obtain sludge samples that were dry yet fresh, this may not always have been reliable due to the apparent haphazard nature of sludge management at many of the selected facilities. In addition, the extent of spatial and temporal variation of pathogens within sludge is uncertain and should be investigated in future studies.

The ability of the pathogens remaining in sludge after treatment to be infectious is uncertain (Lewis *et al*., 2002) and there is some debate about the potential for sewage sludge to present a risk to public health. This debate has focused on whether sludge contains viable pathogens that could be infectious (Lewis & Gattie, 2003). According to Harrison & Oakes (2002), defining a health risk due to residual pathogens in sewage sludge is difficult because of uncertainties in determining actual exposure routes and the designation of an exposed population. There have been few rigorous epidemiological studies of sewage sludge utilization (Lewis *et al*., 2002; NIOSH, 2002; Lewis & Gattie, 2003), and many of the researchers who have studied the exposure health risks have concentrated on wastewater-treatment-plant workers, or workers at composting facilities, where the potential for exposure to pathogens is greatest (Harrisson & Oakes, 2002). Risks have been assessed by considering the type of pathogen that can occur in sewage sludge and how long they can survive under exposed conditions (stockpiles or after spreading). The presence of pathogens in sewage sludge does not necessarily imply that a person would become ill after exposure (Epstein *et al*., 1998; NIOSH, 2002). Illness only occurs when two events happen in sequence: (1) exposure to a sufficient quantity of pathogens from inhalation or ingestion; and (2) the dose of pathogens must be in a sufficient quantity to overwhelm the immune system's ability to contain the pathogen. NIOSH (2002) does not view sewage sludge as presenting an extraordinary health risk and simply recommends that workers exposed to sludge employ good environmental practices and use care in maintaining good personal hygiene. However, although the results of the current study indicated that sludge contained no viable pathogens, the risks to workers and communities that may already be immuno-compromised through HIV-positive status requires further detailed examination.

The analyses carried out above indicate that in terms of pathogen loads, there is apparently a very low risk posed to human health and when considered together with the heavy metal

concentrations, it appears that sludge is suitable for use in agriculture and related activities. However, as mentioned above, the risks to workers and potential end-users who are immuno-compromised still requires detailed examination.

2.3.2.3. The environmental, economic and social implications of current sludge management practices by Eastern Cape STWs

The disposal of sewage sludge poses a potential threat to soil and water systems as well as to human health (Jimenez *et al*., 2002). As a result, the potential impacts of current sludge disposal in the Eastern Cape needed to be ascertained. The risks varied from one STW to another. Table 2.5 provides a summary of the overall risk assessment in terms of the environmental, economic and social risks for each of the nine sample STWs studied in this research. It is important to note that high values indicate a high risk and low values indicate a low risk. The highest possible environmental and economic risk that each STWs could score was 63 and the highest possible social risk was 126. This meant that the highest overall combined risk that a STW could have scored was 252. Detailed results of the risk assessment for each of the nine samples are provided in Appendix II.

Table 2.5: Overall risk assessment results in terms of social, economic and environmental factors for nine sample STWs in the Eastern Cape Province.

Name of	Overall social risk	Overall economic risk	Overall environmental risk	Combined risk
Belmont River Valley	71	45	41	157
Fish Water Flats	56	9	27	92
Driftsands	66	40	38	144
Cape Receife	66	45	38	149
Kwanobuhle	84	47	43	174
Kelvin Jones	52	40	40	132
Despatch	58	40	35	133
Graaff Reinet	71	47	37	155
Cradock	80	47	36	163

Social impacts

The social impacts identified during the risk assessment exercise included potential risk of bacterial, viral and parasitic diseases being directly/indirectly transmitted through the food chain (via animals and/or plants), potential odour problems emanating from the sludge disposal site which might pose a nuisance, location/distance of the sludge disposal site in relation to the nearest human settlement (related to potential nuisance and health risks), use of a potentially polluted water body as a result of sludge disposal by surrounding communities, potential risk of dust/disease being spread by the wind and the presence of flies and other vectors that may pose a nuisance or transmit disease.

The STW which posed the highest overall social risk (Table 2.5) was Kwanobuhle with Cradock, Graaff Reinet, and the Belmont River Valley STWs also exhibiting high overall social risks primarily due to the close proximity of their sludge disposal sites to human or agricultural settlements and the heavy reliance of communities on natural water bodies close to sludge disposal sites for various uses (mainly irrigation and drinking water for animals). Kwanobuhle's sludge disposal site was located approximately 500m from the nearest human settlement, Cradock's 1km from Lingelihle and Graaff Reinet's 1km from Kroonvale and Wolmas settlements. In addition, the Cradock, Kwanobuhle and Belmont River Valley sludge disposal sites were not fenced off and were therefore easily accessible to humans and animals. Indeed, both animals (goats and cows) and/or dung were observed at the sites. Although the ability of these animals to contract disease through contact with sewage sludge, and transmit this to humans through consumption of milk or meat has not been studied, it was regarded a potential health risk.

The effects of bacterial, viral and parasitic diseases and their transmission through the food chain have been greatly studied and opinions vary widely (Muse *et al*., 1991; Shanti *et al*., 1993; Woodyard, 2001; Odegaard *et al*., 2002), with some scholars (Jimenez *et al*., 2002) suggesting that viral and parasitic diseases can be transmitted from sludge-soil-crops-man, while others (Muse *et al*., 1991; Odegaard *et al*., 2002) stated that as long as sludge underwent biological, chemical or heat treatment, long-term storage or any other appropriate process, then disease causing organisms could be killed off. Of potential importance in the spread of disease are vectors such as rodents, birds and insects (US EPA, 2004). While

evidence for the contribution of these vectors to the spread of pathogens from sewage sludge is limited, they were observed at a number of sample STWs and were considered to increase the risk of disease. In addition, microorganisms found in sewage sludge can contaminate ground water causing infectious diseases such as dysentery, typhoid and hepatitis (Holloway, 2002).

Most of the other potential social implications also have either economic or environmental impacts and in order to avoid repetition, will be discussed under these headings.

Economic impacts

The economic impacts identified during the risk assessment included the release of methane gas, a potential energy source, the likelihood that current sludge disposal techniques affect surrounding land-use and the potential wastage of sludge as a resource of economic value. Table 2.5 indicated that all of the STWs except Fish Water Flats exhibited a high overall economic risk.

a) Energy saving

Eight of the nine sample STWs posed a high overall economic risk mainly because they were not collecting the methane produced during stabilization of sludge, and were not using their sludge for any beneficial purpose. As stated earlier, in the process of sewage treatment the "by-product', methane gas, is produced during anaerobic digestion and release of this gas has potentially significant economic implications. If STWs were collecting their methane and used it as an energy source for producing power, they would be able to offset some of the expenses involved in buying electricity to run the plants. For example, Fish Water Flats STW uses the collected methane to run boilers. The exact quantity of energy and revenue saved by STWs that collect and use their methane as compared to those that do not is a potential area for investigation in further studies.

b) Odours and land values

According to the US EPA (2004), odours associated with sewage sludge are typically the primary cause of complaints from communities living near disposal sites. Therefore, another factor that not only had economic but also social implications was the location of STWs'

sludge disposal sites relative to nearby communities. This was mainly due to odour and fly nuisance potential, but also the potential health impacts on residents of surrounding communities. The nuisance value was regarded as inversely proportional to the distance from sludge treatment or disposal sites. Kwanobuhle's sludge disposal site was located 500m from a residential area, Graaff Reinet's sludge disposal site was located 1 km from two residential areas, Cradock's sludge disposal site was located within commonage 1km from a residential area (Lingelihle) and the Belmont River Valley sludge disposal site was located less than 1km from an agricultural settlement. The close proximity of these STWs and associated sludge disposal sites were regarded as having significant social and economic implications.

The link between odour and health is under debate, and Trussel & Jacangelo (2002) stated that, "*…although most people consider bad odours more of a nuisance than a health problem, continuous exposure to strong odours has been shown to adversely affect the health of some people*". For example, in northwest New Jersey, residents of Harmony Township blamed sewage sludge for the air they claimed smelt like diarrhoea, vomit and urine. Lois Markle, a teacher and vociferous opponent of the odours blamed the problem on a farm that accepted sludge, and after years of complaints the state sued one of the operators for air quality violations. According to Markle, "*the only real issue in the public acceptance arena regarding sludge is nuisance: odour and appearance. It is the responsibility of the operators to make sure that they are not creating nuisance conditions and are using the sludge in a "neighbour-friendly manner*" (US EPA, 2004). According to estate agents at Pam Golding in Grahamstown (2005), such complaints can also have a heavy impact on the land values of such areas-with land values declining the closer a place is located to a sludge disposal site. This however is an assumption made by the current study that needs to be investigated in further studies.

c) Use of sludge

Another potential economic risk is that none of the sample STWs except Fish Water Flats and Graaff Reinet, used their sludge for beneficial purposes. As previously indicated (Table 2.3), the other seven STWs either disposed of sludge to landfill sites (Kelvin Jones), on open plots of land (Belmont valley, Kwanobuhle, Despatch, Cradock) or on the sand dunes near the sea (Driftsands, Cape Receife). Fish Water Flats on the other hand transported its sludge by truck

to Coega Brick, where it was used in brick making. Interestingly, some financial cost is involved as the STW pays Coega Brick to take their sludge. There was also a potential financial risk to the Fish Water Flats STW due to cost of clean up in case of accidental spillage that could result during transportation of sludge to the brick factory.

Environmental impacts

The potential environmental impacts that resulted from the assessment included leaching of contaminants from sludge into nearby water bodies resulting in water pollution, the potential risk of air pollution from methane gas, and the presence of birds that could obtain diseases and/or transport diseases.

Based on the above-mentioned risks, the STW which posed the highest overall environmental risk (Table 2.5) was Kwanobuhle with Belmont River Valley, Kelvin Jones, Driftsands and Cape Receife also exhibiting high environmental risks. This was as a result of the potential for air pollution resulting from their management practices and the close proximity of their sludge disposal sites to water resources.

a) Air pollution

Air pollution due to release of methane gas produced during the stabilization of sewage sludge was considered a potential environmental risk. As stated earlier, of the nine sample STWs studied, only one, Fish Water Flats, collected the methane generated. Methane is a significant green house gas, and both air pollution and global warming could be reduced by controlling emission of this material (US EPA., 2004). Researchers found that a reduction of manmade methane by 50% would have a greater impact on global tropospheric ozone than a comparable reduction in manmade nitrogen oxide emissions (US EPA, 2004). South Africa contributes just over one percent of global emissions of greenhouse gases, which, being the equivalent of 10.1 tons per person per year is just above the global average of seven tons (Glazewsky, 2000). This means that if STWs began collecting the methane they produced, they could make a direct contribution to reducing green house gas emissions and global warming. Indirect contributions to the reduction of global warming could be realized if the methane was used as an energy source at the STWs, thereby reducing the demand for coal-generated electricity.

b) Water pollution

Nitrogen from sewage sludge can impact the aquatic ecosystem in a number of ways. In warmer climates (temperatures 20^{o}C and above), nitrifying bacteria place a high biological oxygen demand on water bodies when oxidizing ammonium ions to nitrate (Horan, 1990; Clarke, 2002, Dekker, 2002). This affects the availability of dissolved oxygen to most aquatic organisms. In addition, according to Clarke (2002), ingestion of water with high concentrations of nitrate can be toxic to humans and is thought to be carcinogenic at concentrations of 10-45 mg/l. Furthermore, at a concentration above 30 mg NO_3-N/l, it is particularly toxic to infants and pregnant women resulting in methaemoglobinaemia otherwise known as 'blue baby syndrome' (Horan, 1990; Morrison *et al*., 2001; Clarke, 2002; Dekker, 2002). With regards to ammonia, in solution it is highly toxic to most fish species and other aquatic life and has been found to be lethal even at low concentrations (Morrison *et al*., 2001; Pillay & Buckley, 2001).

The most commonly known result of increased nutrient enrichment of surface waters particularly with nitrogen and phosphorus is eutrophication. Due to the high levels of these nutrients in a water body, there is excessive development of vegetation, generally of the microscopic algae (Pillay & Buckley, 2001). These dense algal 'blooms' then prevent light from penetrating to other submerged plants resulting in their death and decomposition. It is this decomposition of organic matter that places a high demand on the dissolved oxygen which in turn lowers the oxygen available to other aquatic organisms (Morrison *et al*., 2001, Dekker, 2002).

The Belmont River Valley STW disposed of its sludge on an embankment located approximately 50m from the Bloukrans River. Kwanobuhle's sludge disposal site was 200m from the Swartkops River and the Cape Receife and Driftsands sludge disposal sites were approximately 1km and 2km, respectively, from the Indian Ocean. While facilities such as Kelvin Jones are not close to any surface water source, the risk of water pollution arose because sludge was transported 7km from the STWs to a landfill site via pipeline, and this posed a risk for leakage of sludge and its contaminants to the ground water system. In addition, the disposal of sludge with a high water content to landfills as was the case for Kelvin Jones STW, increased the volume of leachate that formed at the bottom of the landfill

and uncontrolled release of liquid leachate can cause severe damage to ground and surface waters (AWWA, 1990).

Since the risk assessment exercise highlighted the threat that leaching of contaminants in sewage sludge, such as nutrients and metals, posed to water resources it was decided to test this finding. This was achieved by conducting a metal and nutrient analysis on one of the freshwater resources, the Bloukrans River, which was located adjacent to the sludge disposal site of the Belmont River Valley STW in Grahamstown. The results of the analysis would provide an indication of whether sludge disposal actually affected the water quality of nearby surface water resources, as predicted during the risk assessment. The reason only the Bloukrans River was selected for nutrient and metal analysis was that of all the sample sites used in the study, this was the only one where sludge was stockpiled within a few meters of a water body and therefore offered the only real opportunity to determine whether contaminants could leach from sludge into the surface water.

Water samples were collected over three consecutive days in September 2004 from two sites along the Bloukrans River. The first samples were collected before the sludge disposal site and the second water samples were collected after the sludge disposal site. All glassware in which water samples were collected had been washed in 5% nitric acid and soaked for at least 4 hours in order to remove adsorbed residues. The glassware was soaked for a further hour in distilled water prior to use. Approximately 500ml of each of the two water samples was collected daily. These samples were brought back to the laboratory and 30ml sub-samples of each were taken, the pH adjusted to <2 and the samples filtered through a 0.45µm nylon syringe filter (Titan) and then analyzed.

The nutrient analysis was conducted using Merck Spectroquant test kits as per manufacturer's instructions and the nutrients that were tested for included: nitrate, nitrite, ammonium and phosphate. The metal analysis was conducted using AA specs analysis (Perkin-Elmer) and sub-samples were analyzed for copper (Cu), cadmium (Cd), nickel (Ni), mercury (Hg), zinc (Zn) and lead (Pb). Two sample T-tests assuming unequal variances were then used to determine whether the levels of each of the nutrients and heavy metals were significantly different in the river water before and after the sludge disposal site. The results are discussed below.

The concentration of nitrates, nitrites, ammonia and phosphates in the river before the sludge disposal site (Figure 2.4) were not significantly different ($p>0.05$) from those after the sludge disposal site. Nitrate was present in the highest concentration in the river water before (10mg/l) and after (15mg/l) the sludge disposal site. This may have been because nitrate is the most soluble form of nitrogen and therefore is relatively mobile in most soil types (Muse *et al*., 1991). In addition, during the breakdown of organic material, bacteria convert organic nitrogen to ammonia. Aerobic conditions facilitate microbial conversion of the ammonia to nitrites and then to nitrates (Horan, 1990; Faniran *et al*., 2001; Fatoki *et al*., 2003). With regards to the phosphate levels, it is important to note that "*much of the phosphate contained in sewage sludge is available in sparingly soluble forms*" (Jimenez *et al*., 2002). The limited mobility of these phosphates provides a partial explanation as to why the levels remained unchanged after the sludge disposal site.

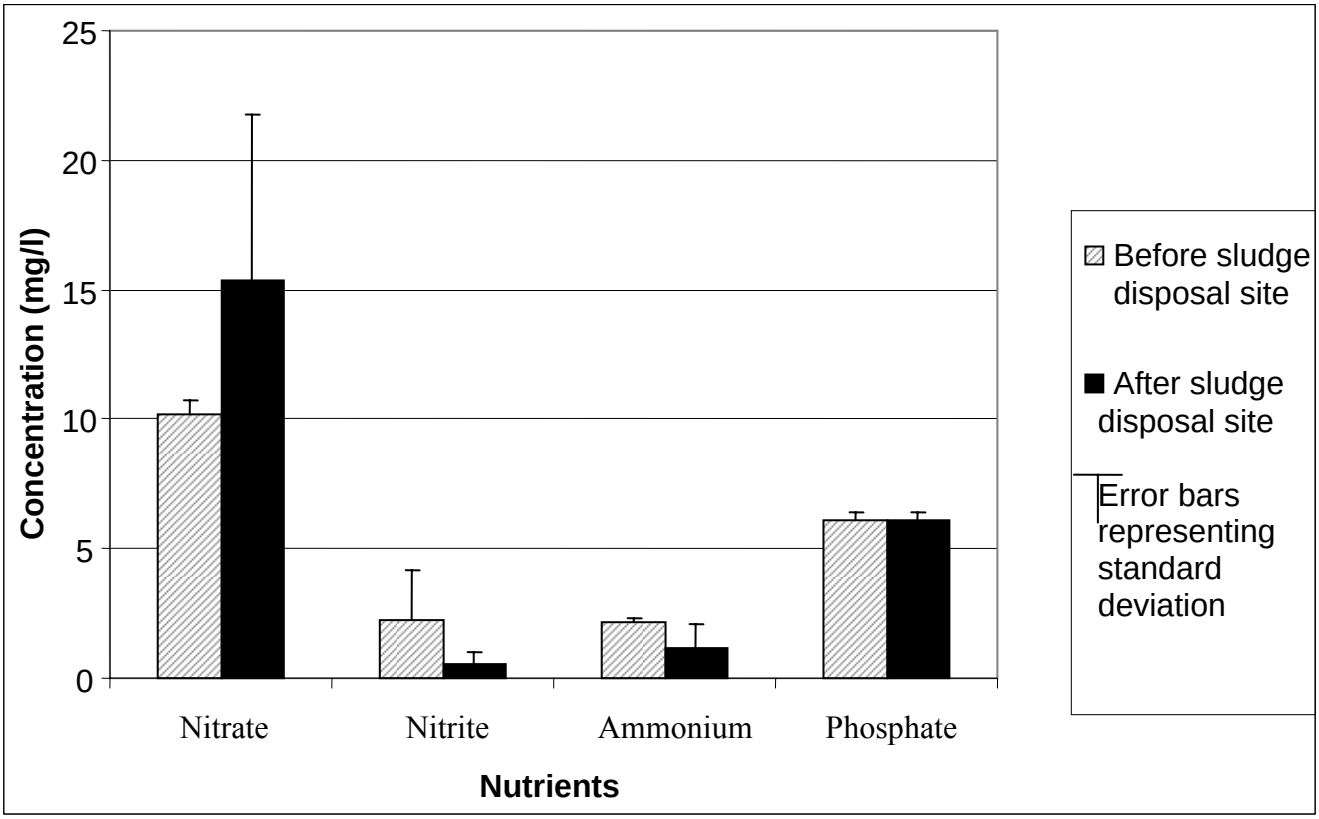

Figure 2.4: Nutrient content (mg/l) of the Bloukrans River before and after the sludge disposal site at the Belmont River Valley STW

These results indicated that sludge disposal by the Belmont River STWs did not pose a significant threat to the Bloukrans River in terms of nutrient loads. Nevertheless, the excess of nutrients resulting from sludge disposed by STWs still needs to be studied further and prevented from reaching surface waters if South Africa is to achieve and maintain its water quality objectives.

Figure 2.5 shows the concentrations of six heavy metals in the Bloukrans River before and after the sludge disposal site at the Belmont River Valley STWs.

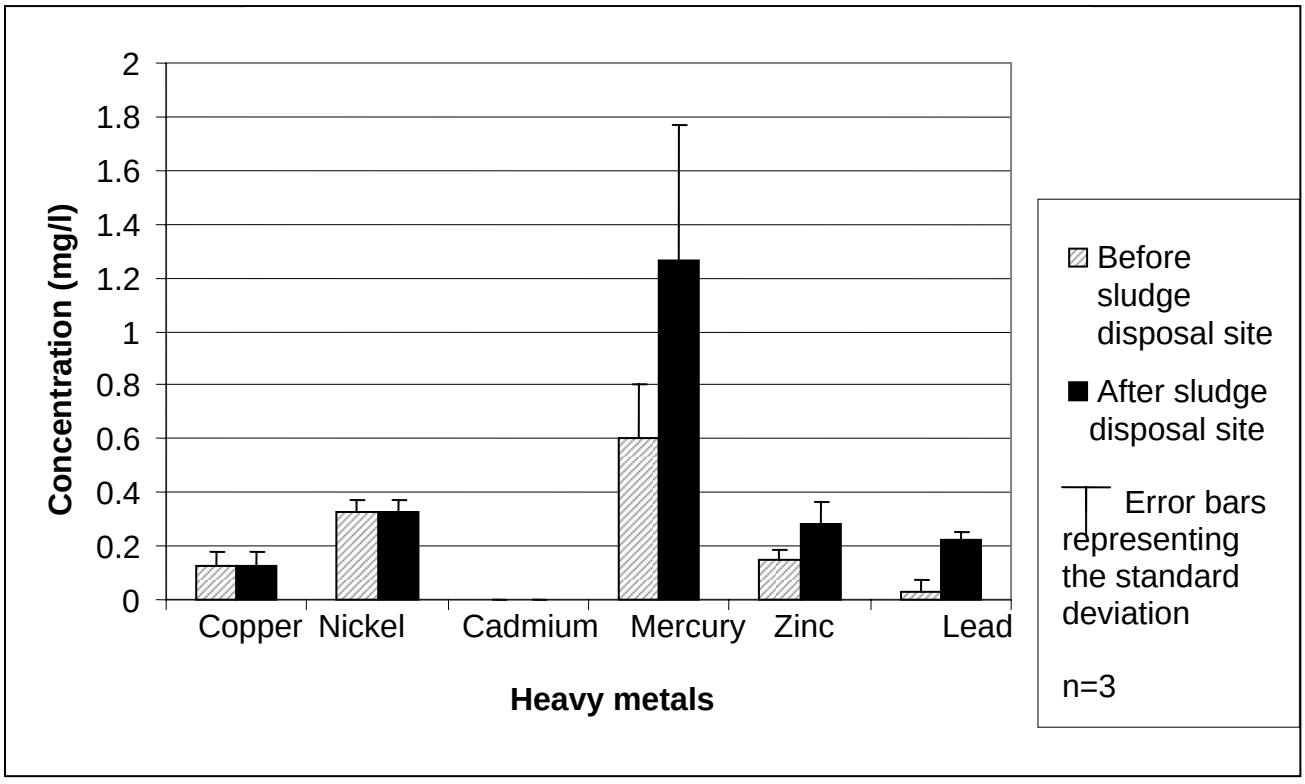

Figure 2.5: Metal content (mg/l) of the Bloukrans River before and after the sludge disposal site at the Belmont River Valley STW.

The concentration of zinc and lead in the Bloukrans River were significantly higher ($p<0.05$) after the sludge disposal site. However, the levels of copper, nickel and mercury were not significantly different ($p>0.05$). These results can be explained by the fact that copper and nickel were not found to be present in the sludge generated at the Belmont River Valley STW (Table 2.4).

However although the mercury levels were not significantly different before and after the sludge disposal site, the levels of this metal were elevated (almost 100% increase). No cadmium was found in the river water before or after the sludge disposal site, as this metal was not present in the sludge at the disposal site. From the above, it appeared that two metals namely, lead and zinc, were able to leach out of the disposed sludge and contaminate the nearby river. Although the increase in the concentrations of the two metals was small, it was nevertheless statistically significant (T-test, $P<0.05$).

Existing data are insufficient to support strong conclusions about risks to groundwater. However, Antoniadis & Alloway (2002) determined that the leachability of nickel, cadmium and zinc was strongly affected by organic matter derived from the parent sewage sludge to the point that enhanced transport caused by soluble organic matter doubled the distance these metals were leached through the soil and water columns. Richards *et al*. (2004) detected associations between organic matter and metals such as sodium, copper, lead, and molybdenum in both soil percolates and the base-flow of nearby streams.

It is also important to remember that sewage sludge is mainly derived from the least water-soluble components of the waste stream. Therefore, as sludge ages and decomposes, all its components are either consumed by biota or transferred to the surrounding media (soil, water or air). Therefore, proper sewage sludge disposal minimizes the impact of sewage sludge and other nutrient sources on water quality (Fatoki *et al*., 2003). According to Faniran *et al*. (2001) and the US EPA (1995), the risks posed to surface and ground waters from sewage sludge are small when appropriate measures are taken. Nevertheless, uncovered stockpiles on bare ground, as found at Despatch and Belmont River Valley, will leach small volumes of concentrated liquid that can affect groundwater with leachate containing elevated concentrations of nitrogen and metals. It is therefore important to ensure that clear guidelines are set out to determine the leachable fraction of these heavy metals into the water system and that these guidelines are enforced.

2.3.2.4. Sludge classification

The results of this risk assessment including fly and odour nuisance, combined with the results on the quality of sludge generated i.e. levels of heavy metals and pathogens present in the sewage sludge samples, made it possible for the sludge from each of the nine sample

STWs to be classified into different types. The PUDSS guideline document (Department of Agriculture *et al*., 1997) states that, "*sewage sludge can be classified into four different types A, B, C, and D in decreasing order of its potential to cause odour nuisance and fly breeding as well as to transmit pathogenic organisms to man and his environment*". The principles they use for differentiation as quoted from PUDSS (Department of Agriculture *et al*., 1997) include:

Type A: Usually unstable and can cause odour nuisances and fly breeding. Contains pathogenic organisms and must meet standards for metal and inorganic contents set out in the PUDSS guideline document.

Type B: This sludge is often fully or partially stabilised and should not cause significant odour nuisances and fly breeding. It contains pathogenic organisms and must meet standards for metal and inorganic contents set out in the PUDSS guideline document.

Type C: This sludge is fully stabilised and should not cause odour nuisances and fly breeding. It contains no viable Ascaris ova per 10g dry sludge, a maximum of 0 salmonella per 10g of dry sludge and a maximum count of 1000 for faecal coliforms per 10g of dry sludge, immediately after treatment (disinfection/sterilisation). The sludge must also meet standards for metal and inorganic contents set out in the PUDSS guideline document. Type C sludge has to be certified to comply with the aforementioned quality requirements. If not certified, this sludge is considered a Type B sludge.

Type D: This sludge has to be certified to comply with the following quality requirements. It must be fully stabilised and should not cause odour nuisances and fly breeding. Contain no viable Ascaris ova per 10g dry sludge, a maximum of 0 salmonella per 10g of dry sludge and a maximum count of 1000 for faecal coliforms per 10g of dry sludge, immediately after treatment (disinfection/sterilisation). The sludge must meet certain metal and inorganic content limits and users must be informed about the moisture content of the sludge and nitrogen, phosphate and potassium contents.

Using these principles of differentiation, the classifications of sludge from each of the sample STWs were determined (Table 2.6). The type of sludge generated at all the STWs listed in Table 2.6, except Driftsands, was of sufficient quality to be used in agriculture. However the

Table 2.6: Sludge types generated at nine sample STWs in the Eastern Cape Province.

Name of	Heavy metals	Pathogens	Odour nuisance	Fly potential	Type of sludge
Belmont valley	Meets requirements	No pathogens	No significant odour nuisance	High	B
Fish water flats	Meets requirements	No pathogens	No odour nuisance	Low	C bordering on D
Driftsands	**Does not meet requirements**	No pathogens	Significant odour nuisance	High	A
Cape Receife	Meets requirements	No pathogens	No significant odour nuisance	Low	C
Kwanobuhle	Meets requirements	No pathogens	No significant odour nuisance	High	B
Kelvin Jones	Meets requirements	No pathogens	No odour nuisance	Low	C bordering on D
Despatch	Meets requirements	No pathogens	No significant odour nuisance	High	B
Graaff Reinet	Meets requirements	No pathogens	No significant odour nuisance	Low	B bordering on C
Cradock	Meets requirements	No pathogens	No significant odour nuisance	High	B

presence of heavy metals and the production of large volumes of sludge may render agricultural use an unsustainable long-term solution. It is also important to note that although some of the sludge samples met the heavy metal and pathogen requirements of Type B or Type C sludge, odour was frequently still regarded as being significant.

The classifications (Table 2.6) suggested that location might influence the overall type of sludge generated at the STWs. The STWs with the biggest design capacities in large metropolitan cities, such as Fish Water Flats and Kelvin Jones seemed to generate the best quality sludge. Of all nine sample STWs selected for in-depth studies, these treatment works also possessed the most sophisticated sludge treatment technologies which probably rendered their treatment processes highly effective and as a result the sludge they generated was of relatively good quality when compared to the other seven sites. Therefore, once alternative uses of sewage sludge have been identified, the sludge treatment technologies may need to be

reviewed in order to result in sludge of a suitable quality.

2.4. CONCLUSIONS

Although the concentration of heavy metals present in the sludge collected from the nine sample STWs selected for in-depth studies in the Eastern Cape Province of South Africa was generally within the limits for re-use, the study indicated sludge from at least one of the nine sample STWs had an unacceptably high mercury content. In addition, although sludge from all sites was free of pathogens, further studies are required to determine if sludge stock piles exhibit spatial and temporal variation in pathogen levels and the associated direct and indirect health risks to HIV-positive individuals still need to be examined in detail. The sludge produced at eight of the nine sample STWs was of a sufficient quality to be used for agriculture. The current study also found that present sludge management practices do pose a threat to the environment, particularly to water resources. This situation can be improved if a disposal system that poses less of a threat to human health and the environment while producing valuable end products could be developed. Chapter 3 of this thesis describes one possible approach to the above-mentioned problem of poor sludge management through the design of an Integrated Waste Beneficiation Facility (IWBF).

CHAPTER 3

CONCEPTUAL DESIGN OF AN INTEGRATED WASTE BENEFICIATION FACILITY (IWBF)

3.1. INTRODUCTION

Current sludge management has negative social, economic and environmental consequences partially due to the perception that sludge is of 'little value' (Viessman & Hammer, 1993). Furthermore, sludge quality remains one of the principal constraints on sludge use particularly as quality standards continue to be tightened and some traditional disposal routes such as landfilling, incineration and disposal on open plots of land coming under pressure while others such as sea disposal have already been phased out in most developed countries. Therefore, the challenge facing sludge managers is to find cost-effective and innovative solutions whilst responding to environmental, regulatory and public pressures.

As previously suggested (Chapter 1, section 1.5), although limited by technical and financial resources, developing countries have the potential to significantly improve sewage sludge management (Foo, 2000; McDougall, 2000; Li *et al*., 2001). Combining certain elements of integrated waste management as practised in developed regions of the world with those traditionally associated with developing countries presents the opportunity to establish waste management systems that are environmentally, socially and economically acceptable and, perhaps, even desirable (Ayres, 1996; Andrews, 1999; VandeKlundert & Anschutz, 2001). Numerous examples of effective re-use or resource recovery being achieved in integrated systems, ranging from low to high-tech approaches, have been reported. Examples include: breweries in Fiji (Foo, 1995), Samoa (Foo & Dalhammar, 2000) and Namibia (Foo, 1998), the sewage-duckweed-fish-banana integrated biosystem at the Mirzapur Farm Complex in Bangladesh (Igbal, 1999), the pig-biogas-duckweed-cassava integrated bio-system in Vietnam (Oron, 1994), Zaozhuang eco-industrial park in China (Chen *et al*., 2001; Li *et al*., 2001), the Eco-House in St. Petersburg-Russia (Yemelin & Mehlmann, 2000), Kalundborg in Copenhagen-Denmark (Enberg, 1995; Cote & Cohen-Rosenthal, 1997) and the Fairfield eco-industrial park in South Baltimore-USA (Cote, 2000). Lessons from these examples suggest that the integrated waste management approach may be able to enhance the economic sustainability of STWs by reducing the cost for disposal of sludge and by generating income

from new value-added products that can be obtained from it.

In addition to the integrated waste management approach, Etnier & Guterstam (1997) and Todd *et al*. (2003) suggested the use of an ecological engineering approach when designing such systems. The latter stated that, "*the task of righting the balance between society and nature is essentially ecological and therefore requires that the wisdom of ecosystems be applied to a fundamental redesign of human support technologies*". The ecological engineering approach uses the natural abilities of living organisms to break down macromolecules and metabolise organic nutrients typically found in wastewater and polluted water bodies. Ecologically engineered technologies have been used for the treatment of point-source waste (South Burlington-Vermont), treatment of non-point-source pollution (Flax pond-Harwich, Massachusetts), architectural integration (Oberlin college-Ohio, Boyne River School and the Kitchener/Waterloo YMCA-Ontario), food production (Intervale-Burlington, Vermont), and the development of agriculturally based Eco-parks (Intervale community enterprise-Burlington, Vermont). Details on each of these ecological technologies can be viewed in Todd *et al*. (2003).

Drawing on these lessons, the purpose of the current chapter was to use an ecological engineering approach to design an integrated waste beneficiation system for improved sewage sludge management in developing countries.

The results presented in Chapter 2 of this thesis showed that current sludge management practices in the Eastern Cape Province of South Africa posed a threat to the environment primarily as a result of the indiscriminate disposal and subsequent leaching of heavy metals contained within sludge into water bodies. In addition although sludge from all nine sample STWs was pathogen free, the potential health risks associated with sewage sludge presented a barrier to use of this material as a fertiliser. In light of these risks, a sludge management technique that employed appropriate technologies able to reduce/remove heavy metals and pathogens from sewage sludge while maximising the benefits obtained from using the nutrients present in it was required.

By employing an integrated systems approach, it was thought that it would not only be possible to provide a solution to poor sludge management, but also substandard effluent quality. Drawing on the results of the study conducted by Mohale (2003), the results of which

were presented in Chapter 2 (section 2.1), the main parameters of concern at the Eastern Cape's STWs were ammonia, phosphate, nitrate/nitrite, and biological oxygen demand (BOD) in treated effluent. Therefore, the proposed system needed to include a technology able to improve the quality of 'treated' effluent while if possible, simultaneously providing STWs with non-regulatory incentives to improving effluent treatment.

While many examples of ecologically engineered systems exist, none appeared to address the specific dual-nature (poor sludge management and inadequate effluent treatment) of the problem being addressed in the current study and while it seemed that an ecologically engineered system would provide a potential solution, there were no frameworks or guidelines on how to approach such a design problem. Therefore, there was a need to first develop a rational design approach to assist in formulating an appropriate integrated system. The objectives of this part of the research were therefore:

- To develop a generic rational approach to the design of novel ecologically engineered systems;
- To use the above rational design approach to develop a conceptual integrated system to address sewage sludge stabilisation, polish 'treated' effluent while at the same time providing additional beneficiation opportunities to users in developing countries.

3.2. METHODS AND MATERIALS

The key steps within the rational approach to the design of an ecologically engineered system are outlined in Figure 3.1. It is essential to first identify the precise problems to be addressed, whether the stabilisation and beneficiation of sewage sludge, or any other waste or sanitation problem. Importantly, the proposed rational design approach is not prescriptive as to the methods to be employed to identify the key problems. In the current study, identification of problems and the identification and screening of individual system components relied heavily on data gathered during the risk assessment as well as literature and expert opinion. The current chapter reports on the use of the rational design approach for the development of the IWBF for sewage sludge stabilisation and polishing of municipal wastewater, and the results of the full technology assessment (TA) of the final design (Step 6, Figure 3.1) are provided in Chapter 4.

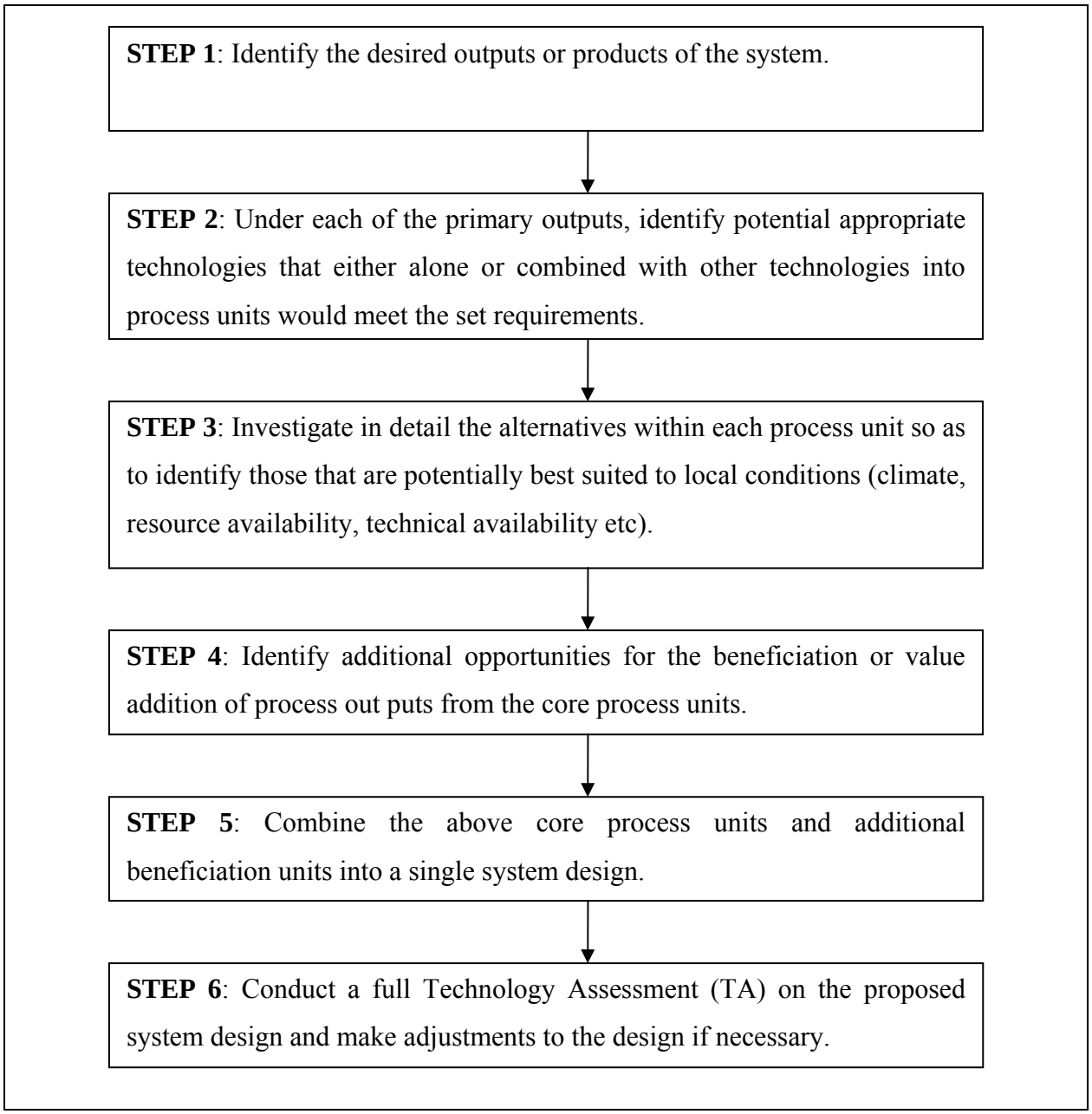

Figure 3.1: Steps followed when conceptually designing the proposed IWBF.

3.3. RESULTS AND DISCUSSION

Based on Step 1 of the rational design approach (Figure 3.1), the desired outputs for the integrated system were to:

- Stabilise sewage sludge (reduce pathogens and fly and odour potential) and to reduce negative social and environmental impacts;

- Polish ‘treated’ municipal effluent by removal of excess ammonia, BOD and pathogens prior to discharge; and
- Generate by-products with a market-value in order to subsidise the treatment process and facilitate local or regional upliftment.

The identification of potentially appropriate technologies which, either alone or combined with others into process units, were able to achieve the above mentioned desired outputs (Step 2) and the detailed investigation of the alternatives in the current context (Step 3) are discussed below. For convenience, the various technologies will be discussed in light of the primary outputs identified in Step 1.

3.3.1. Stabilisation of sewage sludge

There are numerous examples of treatment technologies able to stabilize sludge or convert it into a product with a commercial value and these have been classified according to the current state of the technology, specifically embryonic, innovative or established (Marx *et al*., 2004). Those considered embryonic included adsorbent production, ethanol production and protein extraction for animal food, while ash recycling, brick production, cement-kiln injection, light-weight aggregate production, oil-from-sludge conversion and active sludge pasteurization etc. were considered innovative. The list of established processes is relatively short and includes alkaline stabilization, composting, vermicomposting, land application and land reclamation. Extensive details on each of these technologies can be found in Marx *et al*. (2004).

Of the sludge treatment technologies listed above, composting and vermicomposting seemed the most attractive because they were potentially the least expensive in terms of capital and operational costs, require limited technical expertise for sound operation, have proved successful in developing countries for decades and result in products that have immediate application. The current study has already provided a brief introduction to composting and vermicomposting (Chapter 1, sections 1.4.4.5. and 1.4.4.6 respectively). However, according to step three of the rational design, the actual details of each process unit need further investigation as each may be achieved in a range of different ways. Thus, the specific details of the alternative composting and vermicomposting options are considered below.

3.3.1.1.Composting

General description

Composting is the accelerated bio-oxidation of organic matter passing through a thermophillic stage where microorganisms (bacteria, fungi and actinomycetes) liberate heat, carbon dioxide and water (Conway & Pretty, 1991; Dominguez *et al*., 1997; Sherman, 2002). During the process of composting, harmful substances and toxic products of metabolism are broken down, and destroyed by the heat which reaches a temperature of up to 70^0C at the centre of the compost heap (Conway & Pretty, 1991). Research carried out by Shuval (1990) pointed out that heat treatment of 55^0-60^0C for several hours will ensure a total pathogen inactivation, including the most resistant helminth eggs. The US EPA (2004) guidelines require that during composting, materials reach temperatures of 40^0C for at least five consecutive days or, alternatively, temperatures of 55^0C should be maintained for at least three consecutive days in the coolest part of compost. Suitable conditions may be created by means of a range of alternative composting technologies.

Design of the composting unit

Composting may be divided into two categories based on the nature of the decomposition process, more specifically anaerobic or aerobic. In anaerobic composting, decomposition occurs when oxygen is either absent or in limited supply, whereas aerobic composting takes place in the presence of ample oxygen. As anaerobic composting is a low-temperature process, it tends to leave pathogens intact and decomposition usually takes longer than under aerobic conditions (Sherman, 2002). Thus, although some nutrients may be lost from composted materials when aerobic composting is used, it is considered more efficient and more useful (in terms of reduced pathogen loads) than anaerobic composting for agricultural production (US EPA, 2004). Table 3.1 provides a summary of the different types of composting techniques. Extensive details on each of these techniques can be found in Dominguez *et al*. (1997) or Marx *et al*. (2004).

In deciding the most appropriate composting strategy the factors to consider include, feedstock type, shredding of waste, screening, scale of operation and composting standards (Sherman, 2002). In addition to these, climate must also be considered because relatively cold

Table 3.1: Methods of construction of compost heaps.

Method		How method works
Windrow composting	Naturally aerated	- Raw materials are placed in long narrow piles/windrows which require frequent turning (mechanically) in order to aerate the pile - Process is not easily controlled due to aeration limitations (piles higher than 3m become difficult to aerate). - Malodorous smells easily form due to anaerobic conditions created by the limited oxygen supply. - Increased duration of the composting process. -Sometimes there are problems in attaining the required temperatures for disinfection.
	Forced aerated	-Process is similar to that of un-aerated windrow composting, but aeration is forced by constructing the windrows over aeration channels into which air can be blown, or through which air can be sucked. Alternatively, perforated pipes can be placed in the windrow as it is being constructed. -Mechanical mixing of the piles is recommended to ensure all material is stabilised and disinfected. However, no mechanical mixing of the windrow is possible when perforated pipes have been used as this would damage them. - Large land requirements for the construction of windrows.
Aerated static pile composting	Forced aerated static pile	- The raw material is placed in one continuous pile and as the pile is formed the material is aerated and the composting process starts. - Due to the size of the pile, it is not possible to turn/mix the material during the composting period. Therefore forced aeration is required. - For the purpose of blowing or sucking air through the pile, the system can be covered or enclosed in a building with positive-forced ventilation with air scrubbing for odour control. - A blower provides air to the composting mass, either by: a) bottom suction (draws air through pile by imposition of negative air). Height is critical to achieve uniform aeration and piles must be blanketed with an insulation layer (uniform distribution of temperature), b) bottom blowing (blows air through the pile by imposition of positive pressure). This tends to cool and dry bottom layers, leaving outer layers warm and moist. - Requires less land as higher piles can be constructed, and odours are also contained.
In-vessel composting	Continuous vertical reactors	- Composting is accomplished in an enclosed container or vessel. - Requires both mixing and forced aeration. - Can process large quantities of material - Composting materials are loaded through the top of the reactor and discharged at the base - Oxygenation is provided by forcing air up from the bottom through the composting mass
	Horizontal reactors	- Similar to continuous vertical reactors. Materials are arranged along the length of the unit and the depth never exceeds 2-3m

winters will present problems to open composting systems by affecting temperature control. According to Dominguez *et al*. (1997), in-vessel composting systems (continuous vertical reactors, horizontal reactors) have a principal advantage over windrows and forced aerated static piles because the process can be finely controlled in the former resulting in a shorter duration of the thermophillic stage. In addition, because oxygen is supplied either by turning or by forced aeration, the composting mass can be uniformly oxygenated and the temperature readily controlled (Dominguez *et al*., 1997). However, Marx *et al*. (2004) stated that in-vessel composting, particularly if proprietary equipment and license agreements are involved, is often not viable when compared to the alternatives.

Taking the above-mentioned criteria into account and considering the large amounts of sludge that will need to be composted the current study advocates the use of forced aerated static piles. This is because in such systems, large amounts of sludge can be processed at a single time since higher piles can be constructed. Furthermore, during winter months more heat for the thermophillic stage can be obtained by simply constructing larger piles. This composting technique also has low maintenance requirements compared to any other composting technique and is less expensive and more viable than in-vessel systems. Negative environmental impacts such as odours can also be contained by covering the system. Aerated windrows composting could also have been used but mechanical equipment is required for frequent turning in order to aerate the piles which renders it more expensive than forced aerated static pile composting (Marx *et al*., 2004), a factor which is very important to consider when determining the most appropriate technologies for the majority of developing countries. In addition, windrows higher than 3m also become difficult to aerate (Marx *et al*., 2004) compromising the effectiveness of the process since its success mainly depends on efficient aeration and temperature build up.

Preparation of sludge to be composted

Composting can be carried out with either unstabilized or pre-stabilized sludge. However, a dewatering process is needed before faecal sludge can be composted. As mentioned in the discussion of sludge treatment technologies (Chapter 1, section 1.4.3.3.), dewatering of sludge involves the reduction of the water content. According to Marx *et al*. (2004), for composting the optimum moisture content of faecal sludge is 50%. If values are lower, the composting

process will not take place due to the difficulty in achieving sufficient heat in the compost pile. The dewatering options include embryonic processes (electro-acoustic dewatering, electro dewatering and verti-press process etc.), innovative processes (electro-osmotic dewatering, DAB system, quick-dry filter bed process, rotary press, screw press, second stage dewatering) and established processes (drying beds, belt filter press, mobile belt filter press, chamber press, centrifugation, vacuum filtration and vacuum-assisted drying beds). Details on each of these dewatering processes are reported by Marx *et al*. (2004).

Of the above mentioned options, the current study advocates the use of sludge drying beds, primarily because they are the most widely used method of sludge dewatering in South Africa and in most other developing countries (Marx *et al*., 2004). As a result the costs of preparing sludge for composting would be reduced because STWs can use existing infrastructure. In addition, drying beds have low maintenance requirements, low energy consumption, are less sensitive to sludge variability and can achieve the desired moisture content thereby producing sludge with a higher solids content than other mechanical methods (40-60%). Disadvantages of this method are that sludge has to be manually removed from the drying beds and there may be odour problems. Drying beds also require well-stabilized sludge (reduced microbiological activity) and the retention time of sludge in drying beds will depend on climate (Marx *et al*., 2004) although this may be reduced by up to 50% through frequent turning of the sludge.

Bulking material

It is important to note that if sewage sludge is composted alone i.e. without the addition of other organic bulking material it often requires frequent or continual mixing to prevent sludge from pasting or hardening. Mixing sewage sludge with other organic materials (wood chips, vegetable waste etc.) results in a lowering of the moisture content of the compost mixture and increased airflow due to voids created in the sludge matrix (Dominguez *et al*., 1997). When a larger sized bulking material is mixed with sludge it facilitates airflow which results in a reduction in decomposition time. Kim *et al*. (1986) found that the addition of organic materials in the form of agricultural waste such as barley, straw, rice bran etc. to sludge allowed sufficiently high temperatures to be achieved.

In addition to the above, the nitrogen content of faecal sludge is too high to achieve complete decomposition and by mixing faecal sludge with a bulking material, the C: N ratio can be increased. This is primarily done to ensure optimal conditions for microbial growth in the material being composted. Shuval (1990) suggested a C: N ratio of 20:1 to 30:1 and the US EPA (1999) suggested a C: N ratio that ranges from 25-35:1. A higher C: N ratio (i.e. when more carbon is present and less nitrogen is available) will not create optimal conditions for microbial growth causing degradation to occur at a slower rate and temperatures to remain below levels required for pathogen destruction. Furthermore, as the nitrogen levels increase and the C: N ratio falls below 15:1 nitrogen is lost as ammonia causing unwanted odours (Sherman, 2002).

Since composting increases the amount of material to be managed through addition of bulking agents, a bulking agent that can be screened out and reused is required. According to the US EPA (1999), characteristics such as size, cost/availability, carbon availability, pre-processing requirements, porosity and moisture content must be considered when selecting a suitable bulking agent. Considering the above mentioned characteristics, wood chips seemed to be an ideal bulking agent particularly because they are a good carbon source and may be easily screened out from the final product. However, the disadvantage of using woodchips, particularly during in-vessel composting, is that because they are a good insulator, they can contain the heat released during the aerobic thermophillic stage of composting allowing it to build up to a point where it creates a fire hazard (US EPA, 1999). However, in the case of the IWBF this hazard would be minimised since forced aerated static composting are advocated. It is also important to note that when using bulking materials such as wood, downsizing or chopping up the materials using a shredder is a widely practiced as it increases the surface area available for microbial action and provides better aeration (Sherman, 2002; US EPA, 1999 and 2004).

Sherman (2002) suggested that when forced aerated static pile composting is used, materials should be composted for 21-28 days. Once the composting process is complete, the product will be fairly stable with significantly reduced pathogen levels that can hold nutrients for longer than commercial fertilisers without impacting negatively on the environment. The composted waste, in this case a mixture of sludge and degraded bulking material, can then be

transferred to the vermicomposting process unit for conversion to a higher quality product.

3.3.3.2. Vermicomposting

General description

Vermicomposting is "*a low cost technology system for the processing/treatment of wastes through earthworm consumption*" (Phillips, 1988). Organic wastes are broken down by earthworms, resulting in two useful products, earthworm biomass and a stable non-toxic material with good structure known as 'vermicast'. Vermicast has a potentially high economic value as a soil conditioner for plant growth since it is homogenous, has desirable aesthetics and tends to hold more nutrients over a longer period of time than inorganic fertilizers without impacting negatively on the environment (Kale & Bano, 1986; Edwards, 1998).

Various scientific investigations have established the viability of using earthworms as a treatment technique for numerous solid waste streams including sewage sludge (Edwards, 1988; Hand, 1988; Phillips, 1988; Raymond *et al*., 1988; Harris *et al*., 1990; Logsdon, 1994; Edwards & Bohlen, 1996; Haga, 1998; Marx *et al*., 2004). During vermicomposting, earthworms carry out both physical/mechanical and biochemical degradation processes. The physical/mechanical processes include substrate aeration, mixing as well as actual grinding. The biochemical process is effected by the microbial decomposition of the substrate in the intestines of the earthworms (Bogdanov, 1998). Vermicomposting's potential as a beneficial human pathogen stabilization and management technique for sludge has been addressed (Hartenstein *et al*., 1979; Neuhauser *et al*., 1988; Bogdanov, 1998) and all of these studies agreed with Mitchell (1978) who, in his laboratory-scale experiment, demonstrated that there was a marked reduction in populations of the pathogenic *Salmonella enteriditis*, *Escherichia coli* and other enterobacteriaceae during vermicomposting of sewage sludge by the worm *Eisenia foetida*. Eastman *et al*. (2001), using sludge heavily inoculated with four human pathogen indicators (faecal coliforms, *salmonella spp*., enteric viruses and helminth ova), found that sludge samples vermicomposted with *E.foetida* at an earthworm to biomass ratio of 1:7 and a consumption rate of 1:1.5 decreased levels of all pathogen indicators within 144 hours. They showed significant reductions of faecal coliforms, *salmonella spp*., enteric viruses and helminth ova respectively. However, while worms survive and even flourish in

contaminated wastes, to date there is insufficient information to determine what bio-remediation qualities they possess. Even if there is some uptake of heavy metals, the degree has not been quantified. Similarly, although there appears to be a decrease in the level of contaminants such as PCB's and organo-phosphates, again the data is anecdotal and the method of destruction is not known (Shanti *et al*., 1993).

The specific details of vermicomposting operations including worm species used, worm density and feeding rates as well as the physical structure of the vermicomposting process units vary significantly. As such, these key aspects need to be reviewed before deciding on the most suitable process.

Design of the vermicomposting unit

As with conventional composting, there are various designs of vermicomposting systems ranging from simple land and labour-intensive techniques to more efficient fully-automated systems. Alternatives include wedge systems, windrows, bins, beds, containers and high-tech reactors. Table 3.2 provides a summary of the different types of vermicomposting systems. Further details on each of these can be found in Edwards (1998) and Sherman (2002).

Of the vermicomposting systems presented (Table 3.2), reactors are ideal for large-scale vermicomposting because they can process large amounts of material, feedstock loading and product collection is easier than for the alternatives and, to some extent, this type of system is more commercially viable because fewer worms will be harvested along with the vermicast resulting in reduced replacement costs. However, as reactors may be as high as nine meters and have volumes greater than three cubic meters serious ventilation problems may occur (Sherman 2002). In addition, reactors are not ideal for developing countries because their initial capital costs, overall maintenance requirements and the level of technical expertise required to operate such systems tends to be high. As a result the current study advocates the use of beds/bins as these would be more cost-effective and simpler to operate than complex reactor systems where temperature and moisture could threaten the entire operation. Furthermore, some of the existing drying bed units at STWs could potentially be put aside for vermicomposting, thereby reducing capital costs.

Table 3.2: Types of vermicomposting systems

Type of system	Where it can be used	About the system
Windrows	Indoors, undercover or in the open	- Worm windrows are only up to 0.9m high at most. A thin layer of feedstock 51-76cm (76-152cm in colder weather) is put down weekly - Piles must not built too high because getting the piles too hot will drive the worms away, this is because the higher the piles, the more heat that will be generated - Windrows must be spaced no more than 6m apart so when worms decide to migrate, they can safely make it to adjacent windrows - Large land requirements -Difficult to harvest vermicast from windrows without worms being included, so require a mechanical harvester
Wedge system	Indoors, undercover or in the open	- A modified windrow - Reduced space requirements - Harvesting is easier. No need to separate worms from castings because worms migrate laterally to the wedge-windrow that is receiving fresher feedstock
Beds and bins	Indoors, undercover or in the open	- Take up less space than windrows or wedges because bins can be stacked - Worms are more contained and less likely to migrate - Unlike reactors, worms in beds can burrow into the cooler ground if their feedstock overheats - Units need to be covered to keep out direct sunshine and rain - Harvesting is labour intensive
Reactors	Indoors, undercover or in the open	- Raised beds with mesh bottoms - Temperature and moisture control are very important - Feedstock can be added at the top and collected mechanically at the bottom through the mesh floors

Moisture, temperature and acidity must be kept within certain parameters in these units in order to keep the worms active. The levels of these parameters will to some extent depend on the worm species used. However, according to Sherman (2002), the optimum moisture level for the maintenance of aerobic conditions is 40-45% and would therefore be important to cover the units in order to reduce moisture loss and limit the ingress of rain. The presence of a cover is also considered essential under South African conditions to protect the worms from direct sunlight. Temperature should be within the worm species range because if the temperature is outside this range it will reduce the activity of the earthworms. Mechanisms to maintain the internal temperatures of the beds need to be considered at the design phase, and

may be affected by changing the height of the vermicompost bed within the units. Although worms have a limited ability to modify the alkalinity of their environment, the pH of the vermicomposting material should be monitored and maintained between 6.5-7.0. Worms in beds are contained and less likely to migrate and unlike in reactors, worms can burrow into the cooler ground if their feedstock overheats. The principle disadvantage of using the proposed vermicomposting method however is that harvesting would be labour intensive.

Species of worm

The easiest way to locate the most ideal worm species for use in vermicomposting initiatives is by choosing a local or native species as they would be well-adapted to local conditions (Gowsami & Kalita, 2000). However, it may be possible to locate foreign species that have the same tolerances to local climatic conditions yet have additional favourable attributes. Borges *et al*. (2003), suggested that the earthworm species to be used in any vermicomposting initiative must be able to thrive in high concentrations of organic waste, tolerate a wide range of environmental variations, be epigeic and have a high fecundity (adult/hatchlings ratio).

There are many species of earthworms that have the potential for use in organic waste processing, but relatively few have been used on a widespread scale and researched adequately. Species of earthworms that have been identified as potentially useful in degrading organic wastes include *Eisenia foetida*, *Eisenia andrei*, *Dendrobaena veneta* and *Lubricus rubellus* from temperate areas and *Endrilus eugeniae*, *Perionyx hawayana* and *Perionyx excavatus* from the tropics (Edwards, 1998). The survival, growth, mortality and reproduction of these species have also been studied thoroughly in laboratories, using a wide range of organic wastes (Kale & Bano, 1986; Frederickson *et al*., 1997; Edwards, 1998). Neuhaser *et al*. (1988) studied the growth of *E.foetida*, *E.eugeniae*, *P.excavatus*, *D.veneta* and *P.hawayana* in sewage sludge and concluded that these five species had optimum temperature ranges for growth between 15-25^{0}C and all species produced the most cocoons at 25^{0}C. Of these, *E.foetida* had the highest number of cocoons that survived and grew into hatchlings. Edwards (1988) also studied the lifecycles and optimal conditions for growth and survival of *E.foetida*, *D.veneta*, *E.eugeniae* and *P.excavatus* in animal and vegetable wastes and found each of the four species differed considerably in terms of their response and tolerance to different temperatures (Table 3.3), which would influence the species of earthworm selected

Table 3.3: Tolerance of four vermicomposting worm species to temperature, moisture, nitrogenous wastes and pH.

Species of worm	Temperature tolerance range	Optimum moisture requirements of feed material	Sensitivity to nitrogenous wastes and salts	pH preference
E.foetida	Widest temperature tolerance (0-35^{o} C)	- 80-90% moisture content ideal - Decrease in growth at moisture content below 70% and above 90%	- Die in wastes with ≥ 0.5mg/g of ammonia - Die in wastes with or quantities of inorganic salts ≥ 0.5% - Able to survive in wastes with excess ammonia and salts after removal by composting period and/or wetting	5-9
E.eugeniae	Lower temperature optimum, less tolerance than *E.foetida* at extreme temperatures	- 80-85% moisture content - Decrease in growth at moisture content below 70% and above 90%	- Die in wastes with ≥ 0.5mg/g of ammonia - Die in wastes with quantities of inorganic salts ≥ 0.5% - However, survive in wastes with excess ammonia and salts after removal by composting period and/or wetting	5.0
P.excavatus	Die at temperatures below 9^{o}C and above 30^{o}C	- 80-85% moisture content - Decrease in growth at moisture content below 70% and above 90%	- Die in wastes with ≥ 0.5mg/g of ammonia - Die in wastes with quantities of inorganic salts ≥ 0.5% - However, survive in wastes with excess ammonia and salts after removal by composting period and/or wetting	5.0
D.veneta	Die at temperatures below 9^{o}Cand above 30^{o}C	- 80-85% moisture content - Decrease in growth at moisture content below 70% and above 90%	- Die in wastes with ≥0.5mg/g of ammonia - Die in wastes with quantities of inorganic salts ≥ 0.5% - However, survive in wastes with excess ammonia and salts after removal by composting period and/or wetting	5.0

for South African vermicomposting initiatives. Any species considered for use in South Africa would have to be able to tolerate temperatures in excess of 30^{o}C.

It is clear from Table 3.3 that for South African climatic conditions, the epigeic (i.e. worm that lives at or close to the surface of the soil, feeds on soil, freshly decayed plant matter and animal residues) *E. foetida* had a higher vermicomposting potential than the other worms species due to its tolerance of wide variations in temperature and pH. Ponnuraj *et al*. (1998) and Borges *et al*. (2003) carried out a series of experiments to determine which species of earthworm could tolerate high concentrations of organic matter and may therefore be used in vermicomposting. Potentially suitable South African earthworm species included *L. rubellus*, *E. eugeniae*, and *P. excavatus.* It was found that although the African night crawler, *E.eugeniae*, may be appropriate and is already being used in vermicomposting initiatives (Edwards, 1998), its feeding habits (surface feeder, deposits its casts on the surface) are inappropriate for modern, efficient and less labour intensive vermicomposting systems such as reactors, whereas bottom feeders such as *E.foetida* and *E.andrei* are able to be used in such systems. Furthermore, while *E.eugeniae* is also able to tolerate higher temperatures than *E.foetida*, provided there is ample humidity, it has a narrow temperature tolerance range and cannot survive at temperatures below 7^{o}C making it unsuitable for vermicomposting in countries with wide temperature ranges between winter and summer such as South Africa (0-35^{o}C). Indeed, Venter & Reinecke (1988) and Reinecke *et al*. (1992) concluded that *E.foetida* was the best worm species for vermicomposting not only in South Africa but in other Southern African countries due to its wide temperature tolerance. Therefore, based on the above-mentioned studies *E.foetida* appeared to be the best earthworm for vermicomposting initiatives in South Africa.

Feeding and conversion rates

Edwards & Bohlen (1996) demonstrated that optimum feed rates varied greatly not only with earthworm species but also with feed type. They observed that the amount of waste earthworms ingested seemed to depend largely on the total amount of suitable organic matter, an observation which was corroborated by the earlier work of Neuhauser *et al*. (1980), in the vermicomposting of activated sludge with *E.foetida*. According to Edwards (1998), the feeding rate of worms will be dependant on the rates of conversion, the efficiency of

conversion and whether the main aim of vermicomposting is to produce worm biomass or vermicompost. Furthermore, it is not only important to ensure that worms are fed only what they can convert, but the depth at which they are fed must also be controlled (Edwards, 1988). If too much is fed or if it is fed too thickly, there is potential for anaerobic conditions to develop and this will inhibit worm activity. It is thus essential that the quantity of substrate fed matches the daily quantity consumed by the worms.

Ndegwa *et al*. (1999) found that *E.foetida* had a feeding rate of 1.25kg-feed/kg-worm/day while Harstenstein & Hartenstein (1981) reported that approximately 1g of worm biomass could convert 4g of activated sludge in 5 days and that an input of 28.5 kg of sewage sludge would result in 9.05 kg of saleable fertiliser (feeding rate-0.8kg-feed/kg-worm/day). Riggle & Holmes (1996) noted that worms can consume their own body weight in 24 hours.

Based on experimental analyses from both pilot and full scale operations, Eastman *et al*. (2001) concluded that *E.foetida* had a consumption rate 1.5 times its biomass daily and that the ratio of earthworm biomass to sludge should be 1:7. Box 1 below indicates the formula suggested by Eastman *et al*. (2001) to calculate the quantity of earthworms required for optimum sludge stabilisation.

BOX 1

Kg of sludge ÷ 7 = sludge per day ÷ 1.5 (consumptive rate of earthworms) = kg of earthworms required for stabilisation

From the equation it is clear that the amount of worms required can be determined by dividing the amount of sludge by about 1.5, while each batch could be feed about 7 times the biomass of the worms, only every 144 hours (approx 6 days) so as to maximise pathogen reduction.

Considering the large differences in feeding rates of *E.foetida* established by various studies, the current study decided to calculate the number of worms needed to convert 1ton of sludge using a conservative conversion ratio of 0.5kg-feed/kg-worm/day (i.e. 1kg of worms are required to convert 0.5kg of sludge). Ghosh (2003) stated that one individual *E.foetida* weighs

approximately 1.5-2.5g and Edwards (1998) suggested that 1000 worms require a volume of 0.081 m^3 and these values were used in the current study. Therefore, based on these figures, the conversion of 1ton of sludge (1000kg) required either 800 000 worms (2000kg) weighing 2.5g each in a volume of 64.8m^3 or 1 333 333 worms (2000kg) weighing 1.5g each in a volume of 107.99m^3.

However, according to Sherman (2002), basic conditions namely food availability, space requirements and fouling of the worms' environment control the size of the worm population. The rate of reproduction and onset of sexual maturity are also important as they can be used to determine the optimum feeding and harvesting regime. According to Hand *et al*. (1988), the onset of sexual maturity of *E.foetida* occurs between 3 and 10 weeks after hatching. The reproduction rate of *E.foetida* was recorded as three cocoons/worm/week over a 22 week period by Hartenstein *et al*. (1979) while Neuhaser *et al*. (1980) reported that *E.foetida* produced almost six cocoons/worm/week in mixed manure at 25^oC. Venter and Reinecke (1988) suggested that these differences in production of cocoons may be due to nutritional status of the culture medium. Therefore, if conditions deteriorate i.e. (lack of food, available space less than worms require etc.) worm numbers may drop. This is a very important consideration especially for the proposed municipal-scale vermicomposting process, as large numbers of worms will need to be produced to achieve the desired rates of sludge stabilisation, as well as being able to harvest surplus earthworms for use in the proposed aquaculture step of the integrated process.

Blending

As with conventional composting, research into the optimization of vermicomposting has shown that it is often beneficial to blend sewage sludge with other organic waste sources, primarily to obtain a more favourable C: N ratio (Ndegwa *et al*., 1999; Ndegwa & Thompson, 2001; Sherman, 2002). Although the exact blend ratios used by commercial operations have not been published Ndegwa & Thompson (2001) found the most suitable C:N ratio to be 25:1, but it was recommended that prior to the commencement of full-scale vermicomposting operations, the proposed sludge feed be collected and blended with a range of C:N ratios fed to the worms over a six week period to determine the correct blending ration to ensure maximum attractiveness of the sludge to the worms.

Additional beneficiation opportunities of vermicomposting

As previously mentioned, apart from improved sludge treatment and quality, vermicomposting will also provide additional beneficiation opportunities in the form of vermicast and worm biomass. Live worms from the vermicomposting unit of the IWBF can be sold as live fishing bait, as feed (for fish and chickens), to other facilities wishing to start vermicomposting operations and/or the public for vermicomposting. Alternatively, worms can be processed into dried worm pellets and sold as dried feed for fish and chickens. However, the form the worms take as feed will largely depend on the characteristics of the markets to which they are to be sold. For example, if most fish farmers are growing fish species that can obtain all their nutritional requirements from live worms then worms do not need to be processed and other materials added in order to meet the fishes' nutritional requirements. However, the opposite may also be true in which case it would most likely be easier to dry the worms prior to mixing them with the necessary nutritional supplements and then formulate into suitable pellets or food flakes. The distance to markets and cost of transporting the heavier perishable live worms will also need to be considered separately for each integrated facility.

The other primary product that will be generated from the vermicomposting process unit will be vermicast, a potential fertiliser. Vermicast has been targeted at high value horticulture, viticulture and seedling propagation (Edwards, 1998; Marx *et al*., 2004) and has been recommended to be used in conjunction with standard farm practice, or as an additive to seedling and potting mixes for the nursery industry (Sherman, 2002). According to Edwards (1998), vermicast contains five times more nitrogen, seven times more phosphorus, 1.5 times the calcium, 11 times more potassium and three times the exchangeable magnesium of soil. Vermicast is also rich in humic acid which conditions soils, has a perfect pH balance and contains a number of plant growth factors similar to those found in seaweed. As a result, it is being positioned as a component of rehabilitation processes to address soil degradation (Edwards, 1998). Vermicast commands a price exceeding that of composts, dried manures and mulches. An internet search uncovered many sites marketing vermicast with prices ranging from $2.5-$3.3 (approximately R15-R20) per kg of vermicast. Information regarding the value on the local South African market is scarce and will be the subject of further study. The potential application of vermicast is still undergoing extensive research around the world

in order to establish the long-term commercial value in agriculture particularly horticulture and forestry, land rehabilitation, parks and gardens, golf courses and race tracks and as the benefits of the product become understood and publicised, it is expected that the value will increase.

Although both composting and vermicomposting are able to stabilise sludge (reduce odour, fly nuisance) and reduce pathogens (Dominguez *et al*., 1997; Eastman *et al*., 2001; Marx *et al*., 2004), the current study selected vermicomposting as the primary sludge stabilization technology mainly due to the wider range and potentially greater value of the products that can be obtained from it. The retail value of vermicompost is approximately R 20 000 per tDS, whereas that of compost is an estimated R 400-500 per tDS (Edward, 1998; Marx *et al*., 2004). However, it may still be advantageous to combine both technologies in series so as to maximise pathogen removal and improve the performance of the vermicomposting process unit. According to Ndegwa & Thompson (1999), "*the major drawback in the vermicomposting process is that, in contrast to traditional thermophillic composting (where thermophillic bacteria can raise the material temperature to more than 70^{0}C), the vermicomposting process must be maintained at temperatures below 35^{0}C, because exposure of worms to temperatures above this will kill them…The vermicomposting temperature therefore is not high enough for total pathogen reduction and hence the product will still contain a substantial amount of pathogens*". Logsdon (1994) agreed that composting and vermicomposting might need to be combined so as to reduce pathogen levels in vermicast. Ndegwa & Thompson (2001) then examined the possibility of integrating traditional thermophilic composting and vermicomposting. The work involved combining pertinent attributes from each of the two processes to enhance the overall process and improve the product qualities. The two approaches investigated in the study related to: (i) pre-composting followed by vermicomposting (C-V) and (ii) pre-vermicomposting followed by composting (V-C). The duration of each of the combined operations was four weeks. A comparison was also made with vermicomposting alone (duration: 56 days). The results indicated that the combination of the two processes shortened the stabilization time and improved product quality. Furthermore, the resultant product was more stable and consistent and had less potential negative impacts on the environment. They also found the C-V system to be the better of the two integrated systems because the composting phase which was primarily included for pathogen reduction in the integrated systems was met in the C-V system but not

in the V-C system and although the particle size analysis showed substantial reductions in size in both systems, the C-V system arguably produced the finest and most heterogeneous product. It was also determined that, the overall time of the entire sludge stabilisation process could be reduced in the C-V system by simply regulating the moisture content of the feedstock because then composting would be achieved within a shorter time.

From the discussions above, it is evident that the most appropriate process unit selected for inclusion in the design of the IWBF for stabilisation of sewage sludge-conventional composting followed by vermicomposting is capable of achieving the desired outputs and appropriate to the skills and financial constraints of developing countries. However, a detailed assessment of these proposed methodologies is still required in order to assess their broader sustainability. This will be determined in Chapter 4 of this thesis.

3.3.2. Polishing of 'treated' municipal effluent

'Treated' effluent from STWs can be treated further using tertiary or quaternary treatment methods (Oswald, 1990). The main aim of tertiary treatment is the removal of excess nutrients from wastewater following conventional treatment and these treatment processes may be either physiochemical or biochemical in nature. Examples of tertiary treatment methods include grass plots, shallow lagoons, deep lagoons, slow sand filters, micro-strainers, upward-flow gravel clarifiers, and advanced integrated ponding systems (AIPS). Quaternary treatment is essentially employed for the inactivation or removal of any hazardous substances or pathogenic agents such as viruses, pathogens and resistant bacteria etc. from 'treated' effluent. Extensive information on each of the above mentioned tertiary and quaternary treatment technologies can be found in Horan (1990), Oswald (1990), Heinss *et al*. (1998) and Nameche & Vasel (1998).

According to Rose *et al*. (1996), the microalgal-based AIPS is ideally suited to performing a polishing role at existing STWs in developing countries. This is mainly because the AIPS has relatively low capital and operation costs, low maintenance requirements, requires very limited technical expertise for operation, are highly effective at removing nutrients and pathogens (tertiary and quaternary treatment), are modular (additional units can easily be added in series to meet increased treatment requirements), have low land requirements when compared to stabilization ponds (lagoons) and they produce a marketable by product in the

form of algal biomass. However, their biggest potential disadvantage is that they require sunlight for optimal performance. However, while this could be problematic in colder climates, it is not a problem in South Africa which possesses plenty of sunlight majority of the year. AIPS have been used successfully to treat municipal effluent and wastewaters from piggeries (Costa *et al*., 1999), wine processing (Dekker, 2002), abattoirs (Rose *et al*., 2002) and ammonia-rich tannery effluent (Rose *et al*., 1996). Before assessing the theoretical suitability and compatibility of the AIPS in the IWBF, it is necessary to review the technical aspects of the technology.

3.3.2.1. The Advanced Integrated Ponding System

General description

The process unit operations of the AIPS are similar to those of conventional wastewater treatment plants and include primary sedimentation, floatation, fermentation, aeration, secondary sedimentation, nutrient removal, storage and final disposal (Rose *et al*., 1996) and there have been a number of bulletins and manuals concerning pond design and operation (Marais *et al*., 1961; Marais 1970; Gloyna 1971, Arthur 1983; Middlebrocks, 1983 and 1987; Oswald, 1991; Badger & Price, 1992; Mara *et al*., 1992; Mara *et al*., 1993). Generally, the system is composed of four ponds in series. The first, the primary facultative pond (PFP), is designed to maintain anoxic conditions which facilitate the removal of BOD from wastewater. The PFP is followed by a High Rate Algal Pond (HRAP) in which algal photosynthesis raises the pH of the water which, together with ultraviolet (U.V) light from the sun kills *E.Coli* and other pathogenic bacteria and viruses (Borowitzka, 1989; Bahlaoui *et al*., 1997; Yang *et al*., 1997). Oswald (1991) emphasised the need for the HRAP to be mixed by a paddle wheel to keep the algae in suspension and in so doing decreasing photo inhibition. The HRAP is normally followed by an Algal Settling Pond (ASP) which is designed to promote the settling of algae that can then be harvested and used for a variety of applications including animal feed, plant hormone or for pigment extraction (Chowdhury, 1995; Rose *et al*., 1996). A more extensive discussion on the development, concept and design of the AIPS can be found in Oswald (1988; 1991; 1995) and Rose *et al*. (1996).

Since the influent water to the current study's IWBF would have already undergone conventional treatment in a municipal wastewater treatment facility, effluent will only need to

be polished in order to remove excess nutrients (particularly ammonia) and pathogens. As such, it is proposed that the PFP be omitted and that one or more HRAPs are used for polishing and that algal biomass be removed in an Algal Settling Pond (ASP) (Figure 3.2).

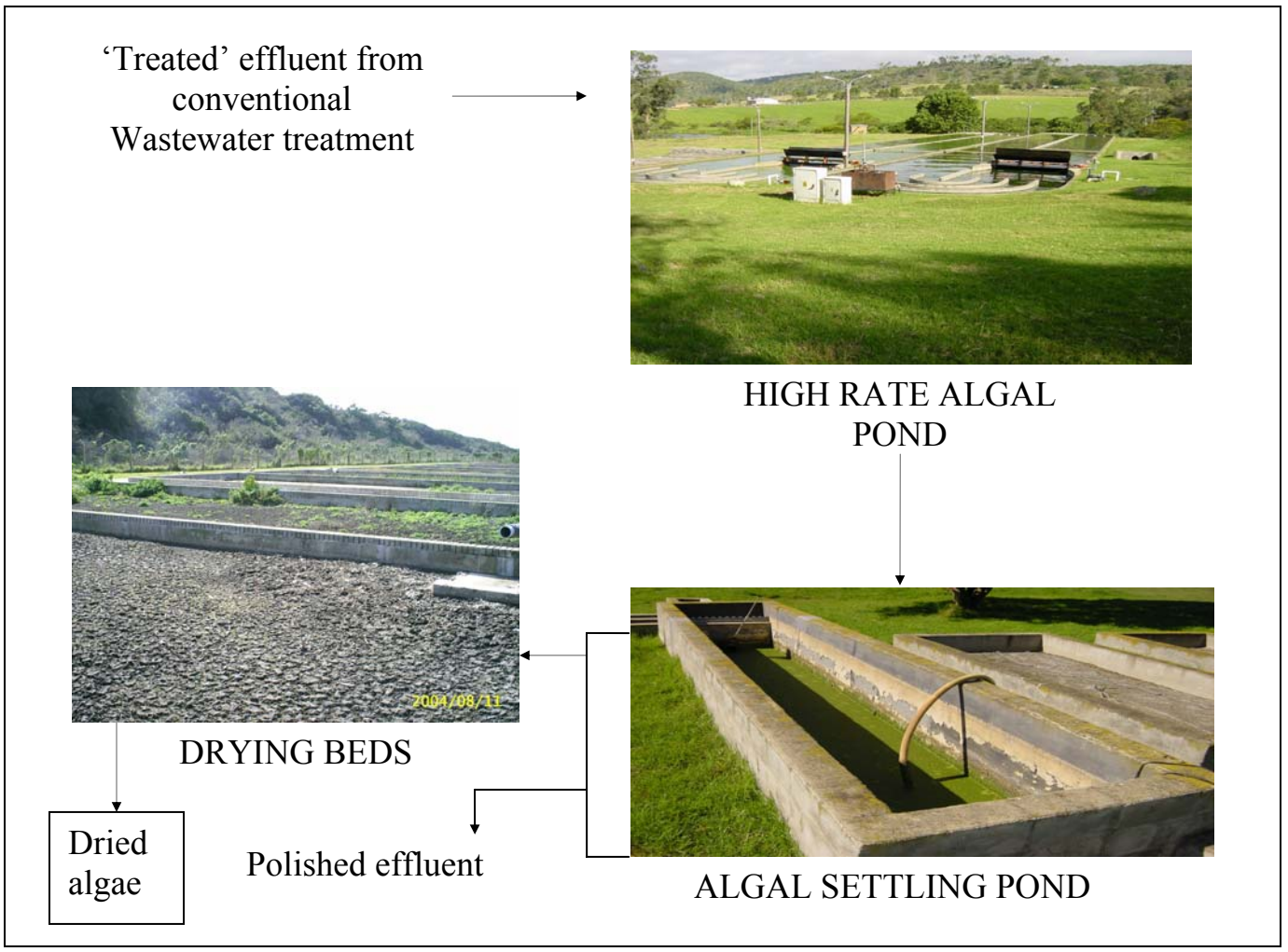

Figure 3.2: HRAP system that will be incorporated in the IWBF.

The specific details on key aspects of the HRAP system's operations including species of algae, size of the ponds required, nutrient removal rates, retention times, harvesting of algae etc. vary significantly. As such, these key aspects will be discussed in more detail below in order to inform the design of this component of the IWBF.

Species of algae in ponding systems

According to experiments conducted by Rose *et al*. (1996), the predominant species of algae

in a HRAP operated in Grahamstown, South Africa were *Scenedesmus*, *Micratinium*, *Pediastrum* and *Actinastrum* spp. *Oocystis*, *Chlorella*, *Anacystis*, *Oscillatoria* and *Ankistrodesmus* spp. and certain diatoms also occurred sporadically mainly during the start-up period. *Chlamydomonas* and *Euglena* spp. were found to be predominant during periods of temporary pond overload. However, it is possible to simply allow naturally occurring species to establish themselves or alternatively, ponds may be seeded with desirable species during commissioning.

Pond size

The size of the HRAP and ASP required will depend on the amount of wastewater requiring polishing. According to the Rhodes University Environmental Biotechnology Group (1997), for a treatment works with a design capacity of less than 1 ML/day, HRAPs with a surface area of 500m^2/pond with a water depth of 30-40cm (to ensure maximum light penetration), and a linear velocity of 20-40cm/second would be required. Ponds of this size would be followed by an AST of 3m^2 and drying beds of 10-20m^2. The typical retention time in a HRAP is 3-5 days with a further half day in the settling tanks (Rose *et al*., 1996; Rhodes University Environmental Biotechnology Group, 1997). After these retention times have been achieved, supernatant can then be released into the receiving source. Detailed information regarding the sizing of ponds and retention times required may be found in Rose *et al*. (1996).

Nutrient removal

Rose *et al*. (1996) documented the performance of the AIPS at the Rhodes University Environmental Biotechnology Experimental Field Station in Grahamstown and monitored nutrient removal rates in the PFP and HRAP over a 25 week period of stable operation (Table 3.4).

It is clear from Table 3.4 that ammonia was reduced by 75% and nitrate and phosphates by 20%. According to Rose *et al*. (1996), "*elevated total COD levels in the effluent of the HRAP appear to exceed the load from the influent into the HRAP, due almost entirely to the production of algal biomass in the HRAP*." Another study conducted by Garcia *et al*. (2002a) found 51.9% and 25% removal of ammonia and nitrate respectively in a HRAP. However Rose *et al*. (1996) found that while the HRAP alone improved the water quality significantly,

Table 3.4: Average performance characteristics of the AIPS plant over a 25-week period of stable operation

(Source: Rose *et al*., 1996)

Parameters	**Influent to PFP (mg/l)**	**PFP effluent/HRAP influent (mg/l)**	**HRAP effluent (mg/l)**	**Final (filtered) (mg/l)**	**General limits according to DWAF (mg/l)**
Ammonia	70	30	7	0	3
Nitrate	7	5	4	3 (2)	15
Phosphate	7	5	4	4 (3)	10
Suspended solids	-	-	150	60 (0)	25
Chemical Oxygen Demand (COD)	950	120	150	80 (60)	75
Coliforms	4.4×10^7	3.9×10^5	5×10^4	1.2×10^3 (0)	1×10^3/100ml

and allows it to meet general requirements as outlined by DWAF for nutrients, the AST was still required to remove additional solids, COD and coliforms. According to Rose *et al*., (2002) removal of phosphate is likely due to the precipitation as calcium phosphate at high pH values while the other nutrients are probably removed primarily through biological uptake and stripping.

An important factor to consider when assessing the efficiency and rate of nutrient removal in the HRAP is climate. Temperature has been regarded as the most important physical factor influencing the efficiency of nitrogen removal because it directly affects the metabolic rate of microorganisms, phytoplankton and algae (Gray, 1992; Ramazanoz *et al*., 1996). Lai & Lam (1995) showed that removal of ammonia, nitrogen and nitrite was more efficient during warm periods particularly in the HRAP. The highest phosphate removal also occurred during summer with the best climatic conditions and harvesting rate. It was ten times lower during winter and was negative during spring and autumn (Chen *et al*., 2003).

Harvesting and Beneficiation of algal biomass.

In addition to polishing 'treated' effluent, the HRAP also provides additional beneficiation opportunities in the form of algae that can be harvested from the AST.

"*Removal of microalgae from a waste stream on a continuous basis is fraught with difficulty*" (Oswald, 1991). Aside from their minute concentrations in water, algae are difficult to harvest because they have a density just slightly greater than that of water and a strong negative charge on their surface so cells tend to remain dispersed (Golueke & Oswald, 1965; Hall, 1985; Shelef, 1987; Nurdogan & Oswald, 1999). Numerous harvesting methods can be employed and include coagulation and settling, dissolved air floatation, screening, filtration, centrifugation, or a combination of more than one of these methods. Table 3.5 provides a summary of each of these harvesting methods, and a more extensive discussion can be found in Oswald (1991).

Settling was regarded as appropriate for the proposed integrated system. This harvesting method was selected because the costs of construction, ease of operation and maintenance requirements of the ASP were relatively low. Once the algal slurry has been pumped from the ASP, it can then be dried using a simple drying bed system. The drying bed may consist of sand floors overlain by permeable matter. Rose *et al*. (1996) suggested that to ensure efficient evaporation and reduce odour formation, the layer of algal sludge in the drying bed should also be maintained at a depth of about 5cm. Although Oswald (1990) suggested that algae should be harvested every fortnight, Rose *et al*. (1996) found that if algal biomass was left in the sump of the AST for too long, conditions become anaerobic and this had a negative impact on the quality of effluent. They therefore suggested algae be harvested from the AST once a week.

There is a growing interest in the use of algae as a stock feed due to its high protein content, and as a fertiliser owing to its high nitrogen content (Chen *et al*., 2003). A number of studies have been conducted on the economic feasibility of these practices, with findings favouring the use of algae over conventional stock feed sources (Chowdhury *et al*., 1995; Yang *et al*., 1997). According to Chowdhury *et al*. (1995), for an estimated yield of 34-1111 kg/ha ash free dry weight, which could be generated by the harvesting of algae in a 1ML pond the

Table 3.5: Methods that can be used to harvest algae.

Method		**About the method**
Settling and dissolved air floatation		-Algal cells tend to clump together entrapping and enmeshing other algal cells while they settle or float. - Highly efficient.
Screening	Vibrating, oscillatory rotary or cascade screens	-Screens are used to trap filamentous algae because their filaments bridge the screen openings and the media can drain away to be discharged or returned to the growth system. - Finer screens (50-100µm openings) are highly effective for *Spirulina* spp., whereas algae such as *Chlorella* and *Scenedesmus* spp can only pass through screens with 5 and 20µm openings respectively. - These screens have low throughput rates and must be continuously backwashed to prevent clogging.
Filtration	Moving filters Rotary vacuum filters	- Can be continuously backwashed. However, they have limited throughput rates and accumulated solids are necessarily diluted by the backwash water.
	Continuous belt vacuum filters	- Successful in removing water from concentrates of filamentous algae such as *Spirulina*.
	Slow sand filters	-Require frequent cleaning and it is a difficult task to separate product from sand. -Only work if algae are first coagulated and flocculated.
	Precoated diatomaceous earth or cellite pressure filters	- Have been used to remove algae from swimming pool water and for emergency drinking water supplies since before World War II. - Clogging is rapid and concentration factors low when used to harvest algae in high productivity cultures.
Centrifugation	- To be economical very large (circumference 84-inches, 213cm-diameter) continuous disc centrifuges are required.	
	Continuous disc centrifuges	- Economical for very high algal material but uneconomical for waste treatment.
	Vertical solid bowl centrifuges	- Have low throughput rates
	Horizontal solid bowl centrifuges	- Are of little value over other concentration systems that cost less because they do not separate microalgae without coagulation and precoating.
Phototatic separation	- Uses light which is absorbed by suspensions of algae, resulting in the formation of a layer of cells that can be removed. - Large-scale system not attempted. - Very expensive.	
Combination	Coagulation followed by dissolved air floatation, highly efficient but expensive.	

potential income can range from R 24 000 to over R 1 000 000 per year. The Rhodes University Environmental Biotechnology Group (1997) estimated production of 75kg/ha/ day dry weight from a 1ML facility with a potential income of R 54 750 to R82 125per year. These figures were calculated using the December 2002 market value for mixed culture algae under the assumption that there was a harvest rate of 50% of total production (Antrobus, 2003). It is worth noting that the actual market value of the algae will, to some extent, depend on the method of harvesting and preparation.

The technologies discussed so far allow the IWBF to be able to stabilise sewage sludge (composting and vermicomposting) and to polish 'treated' effluent (HRAP). Apart from the by-products that will be obtained from these systems (algae, worms, vermicast) there was a need to explore additional technologies that would potentially provide further beneficiation and value-addition opportunities.

3.3.3. Additional beneficiation opportunities

Considering that the primary products of the system were likely to be worm biomass, algal biomass and polished water, inclusion of an aquaculture value-addition step seemed appropriate. Aquaculture is the growth of fish and other aquatic organisms for the production of food or ornamental trade. A discussion on the technical considerations/implications of aquaculture follows.

3.3.3.1. Aquaculture

General description

The use of human excreta for the fertilisation of fish ponds is a common practice in many countries in and around Asia. In China, Taiwan, Hong Kong, Malaysia, Japan and India human excreta is often disposed of into ponds. In West Java, Indonesia, 85% of fish ponds serve as excreta disposal ponds with the use of overhung latrines (Ling, 1977; Edwards & Pullin, 1990; Strauss & Blumenthal, 1989). Common fish species cultivated in these systems include tilapia, Nile carp, Java carp, common carp, kissing gouramy, giant gouramy and Sepat siam. Strauss & Blumenthal (1990) stated that fresh water bodies fertilized with sewage are used in some parts of Asia to produce up to 30,000 tonnes of tilapia and carp every year.

There have also been reports of the cultivation of fish in wastewater pond systems in Europe (e.g. Munich) and Africa (Edwards & Pullin, 1990). Strauss and Blumenthal (1989) suggested that it is likely that fish feed on the phytoplankton which grow on the nutrients from sewage. It is clear, however, that the fertilization of fish ponds with sewage has positive effects on the amount of fish produced. Cross and Strauss (1985) reported that a fish farm in Taiwan had achieved a production of 132 kg/ha/yr and 619 kg/ha/yr in unfertilized and sewage fertilized ponds, respectively.

However, research in Indonesia pointed out that the application of wastewater in fish farming posed health risks for workers and the community (Strauss & Blumenthal, 1990) and there is still a lack of scientific evidence supporting the safe use of sewage-grown fish for human consumption (Ling, 1977; Edwards & Pullin, 1990). This, together with consumer resistance in some cultures towards this fish practice (Cross & Strauss, 1985), indicates that the conceptual design of the IWBF should focus on the production of ornamental and not edible fish.

Provided below are more details on the proposed aquaculture process unit of the IWBF including the species of ornamental fish that should be grown, pond design, water quality requirements, stocking density, fish nutrition and harvesting.

Choice of ornamental fish

For the purposes of maximising the potential benefits that could be generated by the IWBF, the cultivation of koi carp (*Cyprinus carpio*), colourful members of the Cyprinidae family was considered. The reason for choosing this species was that they are high value ornamental fish (R 1795) whose ideal feed is live earthworms and they are best produced in simple earth ponds (Wood, 1993). An alternative species could have been *Carassius auratus* but their commercial value (R 200) is lower than that of koi (Hoffman *et al*., 1998).

Pond design

There are three different kinds of pond systems that could be used to grow koi commercially specifically stagnant ponds, flow through systems and recirculation systems (Table 3.6). The IWBF could use any of these three production systems. However, selection of the system was mainly dependant on the expected capital and operational costs and the income generation

Table 3.6: Types of production systems that can be used to grow koi

Type of system	About the system
Stagnant ponds	-These are usually filled with water before stocking and need to be fertilised to turn water green in order to start the food chain on which the koi will feed - Have low stocking rates - Production can be increased by aerating the water
Flow through systems	- While the basic construction is similar to that of the stagnant ponds, water is constantly flowing into and out of the system. As a result, these systems have improves nitrogenous waste removal and increased oxygen supply. Therefore, stocking density in these ponds can be higher than in stagnant ponds.
Recirculation systems	- The most intensive form of production. - Occupy very small areas - Allow the grower to stock fish at high densities and produce higher yields per unit area - It is essentially a closed system and involves fish tanks, filtration and water treatment systems. The fish are housed within tanks and the water is exchanged continuously to guarantee optimum growing conditions. - Because not all water is 100% exchanged, it is difficult to ensure that all waste products are removed. - Require a high level of management of stock, equipment and water quality

potential. Thus, flow-through systems were considered most appropriate mainly because fish can be stocked at higher densities than in stagnant ponds thereby resulting in higher yields per unit area. Although recirculation systems are able to produce high yields, capital and operational costs are high (Jones pers. comm., 2005). In order to assess the overall viability of the aquaculture step of the proposed IWBF, it was also necessary to review water quality requirements, nutrition and stocking densities.

Water quality

Fish are dependent on their immediate environment for most vital functions and, as a result, are directly affected by changes in the surrounding water. Water quality parameters such as oxygen, temperature, pH, flow rate and nitrogenous waste concentrations ad those mentioned in Table 3.7 must be monitored and maintained to ensure optimal growth of the culture organism (Donaldson, 1990). More extensive details on each of these factors can be located in the references provided in Table 3.7.

Table 3.7: Water quality requirements for fish farming

Water quality requirement	About the water quality requirement	References
Oxygen	-Required for normal physiological functioning -Affected by altitude, water temperature and consumption rate of fish. An increase in any of these factors results in a decline in O_2 levels -Insufficient dissolved O_2 can result in anoxia and loss of stock (mortalities) -Paddle wheels or other types of aerators can be used to infuse O_2 into water	Downing & Merkens, 1955 Davies, 1983 Israeli & Kimmel, 1996 Morshuizen, 2005
pH	-Affected by nitrification (acidifies the water), respiration (release of CO_2 acidifies water) and photosynthesis (use up CO_2 during the day and makes water alkaline) -Each species of fish has its own narrow optimum pH range. Prolonged exposure to the wrong pH can cause stress, increase mucus production and encourage epithelial hyperplasia (thickening of the skin or gill epithelia), acidiosis or alkalosis of the blood and even death -Ammonia toxicity increases with increasing pH -Buffers can be used to physically alter pH. Agricultural lime (calcite or dolomite) increase pH and gypsum or calcium chloride decrease the pH	Chipman, 1934 Downing & Merkens, 1955 Tabata, 1962 Armstrong *et al*., 1978 Thurston *et al*., 1981 Strauss & Blumenthal,1989 Wood, 1993 Israeli & Kimmel, 1996 Yang *et al*., 1997
Temperature	-Affects the availability and growth of the fish. Temperatures below optimum levels prolong the time required to raise the fish to market size and therefore raise production costs, whereas temperatures above optimum levels stress fish resulting in reduced growth, disease and often death -Ammonia toxicity also tends to increase with increasing temperature	Powers, 1920 McCay & Vars, 1931 Herbert, 1962 Hazel *et al*., 1971 Wood, 1993 Jones pers. comm., 2005
Nitrogenous waste	-Ammonia is the main nitrogenous waste and is produced from fish excreta and decaying organic matter such as uneaten food -High levels of ammonia are toxic in gaseous form. They can cause gill irritation and result in death -Sufficient water changes and/or a filtration system (biological/mechanical) are required to deal with both sources of ammonia	Tabata, 1962 Thurston *et al*., 1981 Santhi *et al*., 1992 Wood, 1993 Israeli & Kimmel, 1996 Jones pers comm., 2005
Flow rate	-Critical because determines rate at which resources (oxygen etc.) are brought into the system, and at which excretory products such as faeces, carbon dioxide and ammonia are removed from the system -Can be effected by the provision of inlets (regulate flow from supply canal into pond) and outlets (control discharge of water out of the pond)	Fivelstad *et al*., 1993

Table 3.8 indicates the ideal water requirements for koi farming (Finny Flipper, 2005) in particular and compares these requirements to the quality of 'treated' water after conventional treatment (influent) and 'polished' water leaving the HRAP. The latter data was obtained from Rose *et al*. (1996).

Table 3.8: Ideal water quality requirements for koi farming.

Water quality parameter	Municipal STW effluent	Effluent from HRAP	Ideal quality for koi
Dissolved oxygen	-	-	>5-6mg/l
pH	8.1	9.2-9.5	>6.5-<8.5
Ammonia	70 mg/l	0mg/l	<0.5mg/l
Nitrate	7mg/l	2mg/l	<500mg/l
Temperature	-	-	Range: 5-30^{0}C Optimum: 20-25^{0}C <5^{0}C koi go into hibernation.

Table 3.8 indicates that water leaving STWs after conventional treatment was not of sufficient quality for use in koi farming mainly due to the high levels of ammonia contained in it, whereas for the most part water leaving the HRAP was of sufficient quality for koi farming with regards to factors such as ammonia and nitrates. However, the pH of the water leaving the HRAP was relatively high compared to that ideal for koi, therefore a pH buffer might need to be employed to decrease the pH of water entering the aquaculture process unit. A surplus of dissolved oxygen is also produced in the HRAP (Oswald, 1995) presenting an ideal opportunity for koi farming this is often a limiting factor. However, the problems presented by sub-optimal temperature, dissolved oxygen and pH in the influent to the aquaculture centre are easily overcome by the provision of a heating system, aeration equipment and pH buffers respectively. Although koi's ideal growing season would most likely have been limited to the summer months in most parts of South Africa (Jones pers. comm., 2005) as a result of water temperature, year-round growth can be achieved by the provision of a heating system to ensure commercially viable economic production of koi. Heating may be efficiently achieved through the construction of koi ponds in thermostatically-controlled tunnels. Furthermore, flat shallow ponds with an average depth of not deeper than 50cm would be ideal because koi are

primarily bottom feeders and water in such ponds would be easily warmed. A deep end of approximately 1.2m would provide the fish with a temperature buffer in case water in the shallow became too hot or cold (Jones pers. comm., 2005).

Stocking of ponds

The appropriate stocking density will depend on the culture strategy, size of the pond and size of the fingerlings, among others. Approximately 1000 koi (3-4cm) can be stocked and grown to a market size of 10-12cm in a 2000m^2 pond with a depth that ranges from 0.5 to 1.2m using extensive culture methods (i.e. stagnant water, no flow-through, no aeration, minimal feeding) whereas the same pond could be used to produce five to eight times this number by fertilising the pond and/or the addition of feed and/or aerating the water (i.e. a slightly more intensive production system) (Jones pers. comm., 2005). However, the same pond could only be stocked with 300 to 400 larger koi (12cm) which would be sold at 25-35cm for substantially higher prices.

Fish nutrition

Nutritional requirements are significant when determining the suitability of fish species for aquaculture although the nutritional requirements of most fish are not fully understood (Israeli & Kimmel, 1996). Several factors influence the precise nutritional requirements of koi. Age is an important consideration with young fish requiring a higher percentage of protein than older fish because the growth process requires more amino acid absorption than does maintenance of the body (Israeli & Kimmel, 1996). Water temperature also affects nutritional requirements with low water temperatures (<15^{0}C) slowing growth and lowering protein demand. The amino acid content and digestibility of various protein sources has also been shown to vary (Sabine, 1988; Edwards, 1998; Garcia *et al*., 2002b) and therefore the exact protein source for the feed is important.

Lawrence & Millar (1945) were the first to suggest that earthworms could be considered as a protein source in animal feed. The amino acid composition of various earthworm species has since been studied repeatedly (Harwood, 1976; Sabine, 1978; Yoshida & Hoshii, 1978; Mekada *et al*., 1979; Taboga, 1980; Fisher, 1988; Edwards & Niederer, 1988; Sabine, 1988; Reinecke & Alherts, 1994) and it was agreed that earthworm meal has a high protein content.

However, a high protein content is not the only determinant of the value of the meal as a protein source. The extent to which it satisfies the essential amino acid requirements of a specific species is of greater importance. Essential amino acids are those that cannot be synthesised by the animal itself and therefore have to be supplied in the diet. According to Nesheim & Carpenter (1976), a specific protein source has a high biological value if it contains all the amino acids in the correct ratios. Therefore, in order to utilize earthworm meal as a protein source for koi, the extent to which it satisfied the fish's essential amino acid requirements had to be determined. Extensive details on the amino acids contained in earthworm meal can be viewed in Reinecke & Alherts (1994).

Garcia *et al*. (2002b) conducted a series of experiments to determine the amino acid composition and levels in *E.foetida*. Table 3.9 compares their results to the protein requirements of koi in order to determine the suitability of the species of earthworm being proposed for the vermicomposting step of the IWBF (Section 3.3.3.2) as koi feed. Table 3.9 is not an exhaustive list of all the amino acids found in *E.foetida* but is restricted to those required by koi.

It is clear from Table 3.9 that *E.foetida* contains at least 50% of the dietary amino acid requirements of koi. The levels of the amino acids phenylalanine, methione, lycine, threonine and trytophan present in *E.foetida* are not sufficient to meet those required by koi. In particular, the levels of phenylanine and methione are 81% and 53% lower respectively than the required levels. Although some of the deficiencies could be corrected partially by the inclusion of algal biomass in the feed, certain amino acid supplementation would be required.

Feeding rates of the fish

The feeding rate is computed as a percentage of the estimated animal biomass in the pond, with higher rations given when the animals are small and gradually decreasing as they become bigger (Jones pers. comm., 2005). The daily feeding rate (live biomass) for most fish species usually starts at 5% of estimated biomass and decreases to a low of 2% towards harvest (Strauss & Blumenthal, 1989). Using the feeding rates given by Strauss & Blumenthal (1989), assuming that a single koi weighs 1kg, then its daily feeding rate would start at 0.05kg feed/day and if towards harvest the koi weighed 3kg then its daily feeding rate would then be

0.06kg feed/day.

Table 3.9: Comparison between the amino acid composition of *E.foetida* and the microalgae *Spirullina* with those required by koi.

Amino acid	**Content in *E.foetida* (g/100g protein)**	**Content required by koi (g/100g protein)**	**Content in algae-*Spirullina* (g/100g protein)**
Arginine	4.36	4.3	**3.8**
Histidine	2.87	2.1	**1.0**
Isoleucine	3.67	2.5	**3.0**
Leucine	6.02	3.3	**-**
Lysine	**5.21**	**5.7**	**3.1**
Methione	**1.47**	**3.1**	**1.1**
Phenylalanine	**1.26**	**6.5**	**2.7**
Threonine	**3.66**	**3.9**	**3.0**
Trytophan	**0.56**	**0.8**	1.1
Valine	4.48	3.6	**3.4**
Other nutritional requirements			
Nutrient	**Content in E.foetida (mg/kg)**	**Content required by koi (mg/kg)**	**Content in algae-*Spirullina* (mg/kg)**
Calcium	1.69	Unknown	3700
Magnesium	0.11	0.05	6300
Phosphorus	1.17	0.6	8600
Potassium	1.16	Unknown	13200
Sodium	0.50	Unknown	681

Note: Those amino acids not present in sufficiently high concentrations in earthworms are indicated in bold.

Harvesting and transportation of the koi

Harvesting of koi is a skill that requires experienced labour so that it can be carried out in a manner that is quick, safe and as stress-free as possible, and usually involves the use of hand nets (Fevolden *et al*., 1991). Much larger seine nets are required when harvesting koi from earth production ponds and typically 80-90% of fish will be removed this way (Beitinger, 1990) with the rest of the fish only being harvested upon draining of the pond. Draining the

water out of the pond will allow the fish to gather in the sump (deep-end) making removal easy.

Once caught, the fish must immediately be placed into plastic bags that contain an anesthetic (2- phenoxy ethanol) and salt. Salt acts as a disease treatment and also assists in kidney function, because it stabilizes the gradient between the fish and its environment (Donaldson, 1990). Koi can then be selected and screened with a large percentage usually being culled. However, this depends on the variety/strain and the quality of the brood stock. The majority are sold as small pond fish (10-12cm) to pet shops, and the best specimens kept and grown to a larger size when they will be marketed for substantially higher prices. After harvesting, the fish are usually shipped in plastic bags filled with oxygen-saturated water. The chemical zeolite can also be used because it helps in the absorption of ammonia and in so doing reduces nitrogenous waste so that no poisoning of the fish occurs (Jones pers. comm., 2005).

Market for koi

The costs of retailing of koi are largely dependant on the size and sex of the fish. Larger fish and females sell for more than small fish and males. Prices can range from R 1795 for a single 32cm koi to R 13795 for a 55cm koi (Cape Koi Aquarium, 2005). However some good quality koi can be sold for up to £7000 (approx. R84, 000) (Jones pers comm., 2005). The market availability for koi was determined as part of the TA and will be reported in Chapter 4.

Having discussed the various appropriate technologies that can be used to stabilise sewage sludge (composting and vermicomposting), polish 'treated' effluent (HRAP) while simultaneously providing valuable products (vermicast, algae, koi), Step 5 of the rational design approach was to attempt to merge all the selected technologies or process units into a single integrated system, the IWBF. The preliminary conceptual design of this facility is described in section 3.3.4 below.

3.3.4. Conceptual design of the IWBF

Figure 3.3 indicates the conceptual design of the IWBF. The primary inputs into the system will be 'treated' effluent, sewage sludge and the outputs will be polished effluent, vermicast, algae, and fish. Worms will be produced as an intermediary product but will also be

consumed within the system. The main technology stages will be;

- A HRAP (multiple) and ASP;
- Composting stage;
- Vermicomposting; and
- Aquaculture

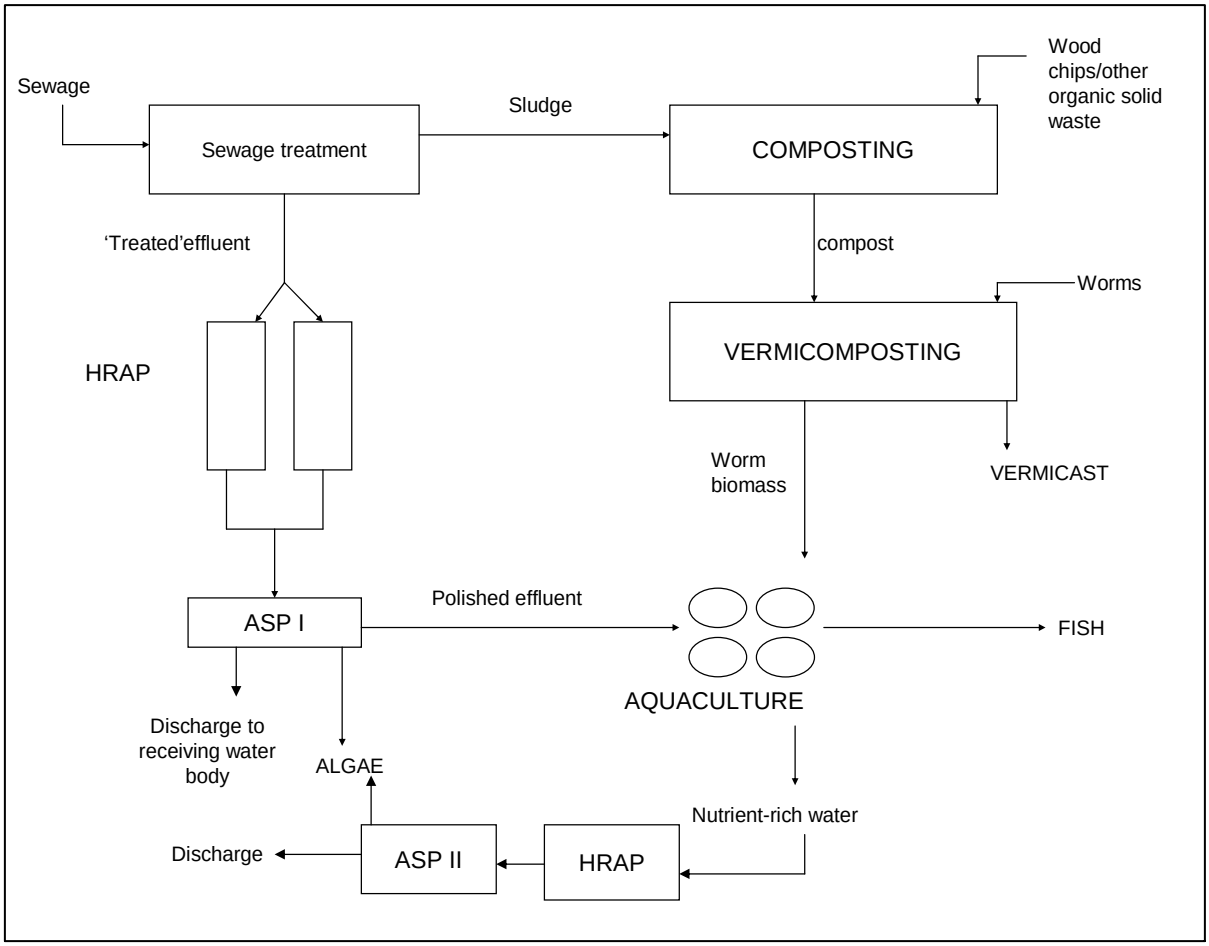

Figure 3.3: The design of the Integrated Waste Beneficiation Facility (IWBF).

The first of the two primary inputs, 'treated' effluent, will undergo polishing within the HRAP. After polishing, this water will be discharged to a receiving body with the required volume being sent to an aquaculture facility where koi will be grown. The algae from the HRAP will be harvested from the ASP, dried and sold as stock feed or fed to fish. The second input, sewage sludge, will be composted and then sent to a vermicomposting unit. In the vermicomposting unit, composted sterile sewage sludge will be converted by worms into worm biomass and vermicast. Worms from the vermicomposting unit will then be used as live

feed for the koi growing in the aquaculture facility and any excess worms sold live or in a dried form. Vermicast will be sold as fertiliser to a range of different market sectors e.g. agriculture and horticulture.

3.4. CONCLUSIONS

In Chapter 3, the use of the rational design approach was applied to the design of the conceptual IWBF for the improved management and beneficiation of sewage sludge. By firstly identifying the key objectives of the system, it was possible to identify potential technologies and conduct a preliminary screening process to eliminate those alternatives that were unlikely to be practical in the target setting. The later "screening" required at least some understanding of the local limitations such as availability of skills and finances. The product of the design process was an integrated process train that required a more detailed assessment to determine the likely sustainability at the target sites. This was determined using a TA which would assist in assessing the sustainability of the IWBF in various contexts and would entail the assessment of its possible environmental, economic social and technical impacts as well as potential barriers to implementation. The result of the TA is presented in Chapter 4.

CHAPTER 4

TECHNOLOGY ASSESSMENT OF THE IWBF

4.1. INTRODUCTION

The conclusions of Chapter 2 of this thesis indicated that current sewage sludge management practices in the Eastern Cape Province of South Africa posed a threat to environmental and, potentially, human health. The current study then attempted to address this problem through the rational design of an Integrated Waste Beneficiation Facility (IWBF) based on the principles of ecological engineering. The proposed system was designed to meet predetermined outputs (improved sludge management, polishing of municipal effluent and beneficiation of waste streams) while taking the considerable limitations associated with developing countries into consideration. However, despite the reliance on relatively simple, robust process units in the final process design a detailed technology assessment (TA) was still required in order to determine possible barriers to implementation, with an emphasis on those barriers that were context-specific. Dunmade (2002) suggested that new technologies, such as the IWBF described in the previous chapter, must be thoroughly assessed prior to implementation because the success of any technology is context-specific and may differ from one location to another, especially in developing countries. Additionally, Van Eijndhoven (1997) suggested that, "*solutions to global problems which threaten the notion of sustainable development can only be realized through technology, and the indispensability of TA comes due to the need to avoid unwise and unfounded decisions in selecting the right technology*". Therefore, the TA step should always be regarded as an essential stage of the rational design of any integrated system in order to allow developers of such systems to make alterations to original designs prior to potentially costly construction and pilot-scale testing.

The United Nations Environmental Program (UNEP) broadly defined a TA as "*a category of policy studies, intended to provide decision-makers with information about the possible impacts and consequences of a new technology or a significant change in an old technology. It is concerned with both direct and indirect or secondary consequences, both benefits and disadvantages, and with mapping the uncertainties involved in any government or private use or transfer of a technology*" (CEFIC, 1997). Despite the lack of a generic methodology for performing TAs, there is consensus about the importance of assessing, selecting and applying

technologies that satisfy the global desire for sustainable development. Bracken *et al*. (2005) suggested that the success of technologies, particularly in the sanitation and wastewater treatment sectors, cannot be realised if the concept of sustainability is not considered when conducting assessments to identify potentially appropriate solutions. They further suggested that "*one very practical way in which to achieve a more holistic view…..allowing more sustainable solutions to be reached…..is by using sustainability oriented criteria for comparing and assessing sanitary systems*".

Development of sustainability criteria, indicators or metrics usually entails selecting "key measures" for collecting information which may be environmental, economic, or social. However, the challenge is to select and develop meaningful sustainability-oriented criteria, indicators or metrics that are not too complex yet sufficiently generic and adaptable enough to address the particular assessment needs of individual projects and, in so doing, provide reliable and accurate information against which they can be measured (Callens & Tyteca, 1999). It is also important to remember that criteria, indicators or metrics in themselves should not become more important than the process nor be used as a basis for reducing the importance of a parameter which does not readily lend itself to measurement (Wood, 1997; Callens & Tyteca, 1999).

Traditionally, the main criterion used for assessing technologies and making choices between alternatives was economic efficiency. As a result, cost-benefit analysis (i.e. accounting for and comparing in the same analysis all the expected costs and benefits of a technology for a particular project/technology) was the main tool being used (Baas, 2000; Hays, 2001). Cost-benefit analysis, however, proved to be ineffective since translation of all costs and benefits into a single monetary value proved to be problematic especially since there are no natural prices for a healthy environment (Serafy, 1991; Berg, 1994).

Recently, there has been a trend towards TA focusing primarily on environmental impacts as is promoted by the UNEP's Environmental Technology Assessment (EnTA) (CEFIC, 1997). As defined by this program, "*EnTA is a process that can assist decision-makers make informed choices that are compatible with sustainable development by examining and describing the environmental implications of new technologies*" (UNEP, 1998b). The extent of issues covered in TA also naturally requires that a range of tools be applied. In the case of

EnTA, environmental management tools such as Environmental Impacts Assessment (EIA), Life Cycle Assessment (LCA), and Risk Assessment (RA) are considered appropriate and useful for deriving the information required for the TA (CEFIC, 1997; UNEP, 2001).

A related assessment technique, the Cleaner Technologies Substitute Assessment (CTSA) methodology, was developed by the US Environmental Protection Agency "*to provide comparative cost, risk and performance information on technologies based upon readily available information and using simplifying assumptions and conventional models to provide general conclusions about various technologies*". However, CTSA is not a rigorous assessment and cannot be used to describe the absolute level of risk associated with particular technologies because results often represent case studies and these case study scenarios may not be representative of common practices. For instance, data on performance are reported from real world performance demonstrations conducted in model facilities that may or may not be representative of the specific operation (Hays, 2001).

In addition to the above-mentioned methods, a computerized model concept for systems analysis of waste management systems known as Organic Waste Research (OWARE) was developed in Sweden to contribute to the development and practice especially of environmentally focused TA since 1993 (Callens & Tyteca, 1999). OWARE is characterized by material and substance flow modeling of the technological system, life cycle perspective and quantification of potential environmental and economic impacts (Blair, 1994). However, the OWARE model like CTSA tends to base its choice of ideal technological alternatives on scenarios which may not be particularly representative of specific technologies and like most TA methods, it is best used when there is more than one technological option to choose from i.e. it is largely comparative. Furthermore, OWARE is most appropriate when quantitative data is available so as not to be ambiguous and subjective. This also makes it unsuitable for use in the majority of developing countries which lack the necessary finances to collect detailed quantitative data and frequently have inadequately developed research and development activities. Additionally, it is also unsuitable for conducting a TA of a "theoretical" proposed system that is still in the design phase, although information on each of the individual process units may be readily available.

Based on the above, the primary objectives of this part of the study were to:

- Develop a modified set of criteria (sustainability criteria categories) for the assessment of waste management technologies being developed and destined for use in developing countries;
- To assess the sustainability of the proposed IWBF concentrating on desirable and undesirable environmental, social, economic and technical impacts/risks at the nine study sites;
- To determine the potential barriers to implementation of the IWBF at the nine study sites;
- In line with the above objective, to identify those aspects of the IWBF that will be influenced by location and, in particular, distance from metropolitan cities; and
- To identify aspects of the IWBF that require further investigation prior to implementation.

4.2. METHODS AND MATERIALS

Based on the discussion above, none of the existing TA methodologies was considered entirely appropriate by itself and thus a suitable method was formulated. This method was largely based on EnTA methodology (importance of environmental and social impacts) but included elements of the CTSA e.g. performance assessment. The resulting method consisted of six steps as shown in Figure 4.1, and was used to assess the likely sustainability of the IWBF. The biggest perceived shortcoming of the existing methods was that they did not adequately assess social and technical sustainability and did not explicitly consider the local context within which technologies are to be implemented.

As with the EnTA and CTSA methodologies, the TA process requires a detailed description of the technology but, added to this is a list of the desired goals/outputs of the technology (Step 1, Figure 4.1). However, with regards to the current TA, the detailed description of the proposed technology has already been provided in Chapter 3 and will not be repeated. As required by Step 2 (Figure 4.1) the scope of the current TA was limited to the immediate impacts of the inputs and outputs of the IWBF from construction to operation but excluded raw material extraction and processing. Although it was suggested that a pre-determined set of sustainability criteria be identified, unlike most TA methods, these criteria were not rigid and could be expanded, reduced or replaced prior to assessment depending on the perceived

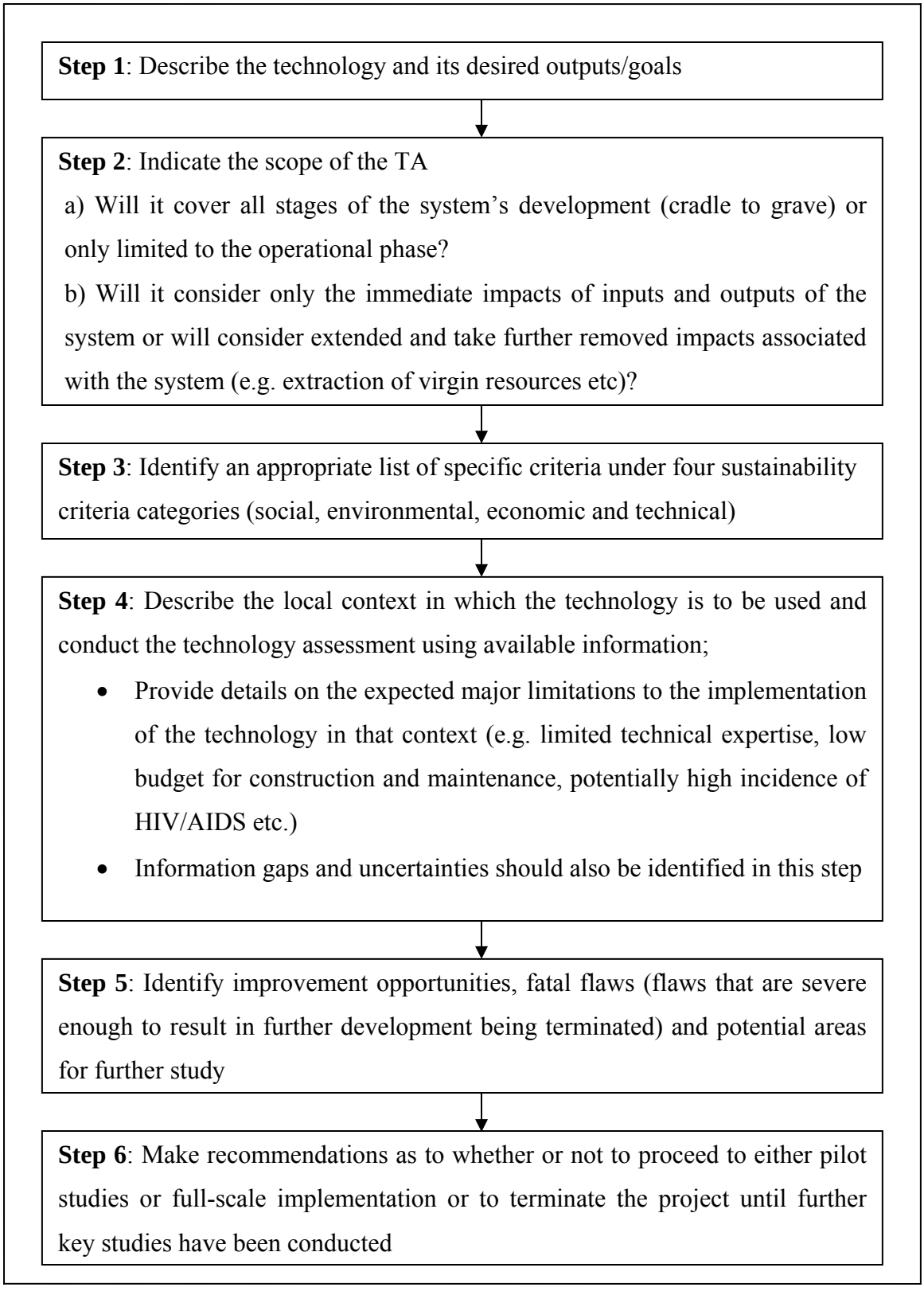

Figure 4.1: Suggested methodology for the assessment of any technology destined for use in developing countries and was applied to the IWBF

local relevance. Similarly weighting of the various criteria, if applied, would also be dependent on the perceived or agreed relative importance of the criteria.

The range of specific criteria used to assess the IWBF are shown in Table 4.1. Criteria were selected based on the results of Chapters 2 and 3 of the current research together with those from a range of literature sources (Salomon *et al*., 1994; US EPA, 1995; Pearson *et al*., 2001; UNEP, 2001; Dunmade, 2002; Bracken *et al*., 2005). The criteria listed were selected primarily because they were all considered to have contributed to the success or failure of many technologies around the world including those in the sanitation and wastewater sectors.

The selected criteria against which the IWBF was evaluated were placed under four broad sustainability categories (technical, social, environmental and economic) which are considered to provide a more accurate and holistic "picture" of the likely sustainability of any technology (US EPA, 1995; UNEP, 2001; Dunmade, 2002; Bracken *et al*., 2005). Overlaps between the categories were noticed with, for example, specific criteria mentioned under the technical category such as the availability of local servicing resources possibly also fitting under the economic and social categories. The list of criteria used in the current study was not simply a checklist to which scores could be applied to derive a final overall score that would theoretically have provided a "measure" of sustainability relative to some theoretical maximum score (indicating a "perfectly sustainable" system). Instead, the checklist was used to guide the qualitative assessment of the embryonic technology, in this case the IWBF. Only through such a qualitative assessment, would it be possible to achieve the aims of the assessment i.e. to determine whether the proposed technology would have any significant negative social, environmental and economic impacts and whether they were any significant barriers to implementation. Such a qualitative assessment would then inform the modification of the preliminary design prior to pilot-scale testing.

The context of the current TA was the nine sample STWs which had been used earlier for in-depth studies on sludge management in the Eastern Cape. Although detailed descriptions of STWs are provided in Chapter 2 (section 2.2.2), additional details on each of the STWs' local contexts required by the TA of the IWBF will be provided in this chapter as the analysis proceeds.

Table 4.1: A summary of the criteria, divided into four sustainability categories, used to assess the sustainability of the proposed IWBF technology

Sustainability criteria categories	**Specific list of criteria**	**Method of data acquisition**
Technical sustainability	Performance assessment, product analysis, process efficiency, process robustness, accessibility to technical expertise and component parts.	Literature review Consultations with experts on each of the IWBF process units
Social/cultural sustainability	Job creation, education through training, health related issues, health-related legal requirements, public acceptability (awareness, system perception, appropriateness to social and cultural influences and changes in social structures).	Literature review Questionnaire survey
Environmental sustainability	Resource demands (land, infrastructure, energy, chemicals), environmental-related legal requirements (impact on water, land, air, and biodiversity).	Theoretical environmental risk assessment Literature review
Economic sustainability	Value of products, cost-benefit analysis, affordability, location.	Cost-benefit analysis Semi-structured interviews with municipalities, STW managers and potential users of products

Data used to conduct the TA of the proposed IWBF was obtained from a number of sources as indicated in Table 4.1. Based on preliminary inquiries, one of the areas where very little information was currently available was the potential local (Eastern Cape Province, South Africa) market value of the vermicast produced by the system and the attitude of potential users. This information was regarded as important and was obtained by means of questionnaires (Appendix IV) administered to 20 plant nurseries and 20 farmers located within a 100km radius of the nine sample STWs. Both specialist and generalist nurseries were surveyed as well as subsistence and commercial farmers who grew a range of crops from pineapples, to citrus and deciduous fruit, tomatoes, chicory and tea. The questionnaire explained to respondents the nature of the vermicast product and respondents were asked to indicate whether they were presently using vermicast on their establishments, and if not, whether they would be willing to use or sell it. Respondents were also required to indicate an approximate price at which they would be willing to buy or, in the case of nurseries, sell the vermicast. As indicated in Table 4.1, most of the remaining information was obtained either from published reports and articles or by means of semi-structured interviews with experts on each of the IWBF's process units. Interviews with municipal officials and STW managers were used to obtain information on aspects such as the potential pool of employees at STWs in the Eastern Cape Province.

4.3. RESULTS AND DISCUSSION

4.3.1. Technical sustainability

It was decided that the technical sustainability should be conducted first as detection of any technical barriers to implementation would result in either significant modification or rejection of the technology. In either case, assessment of the other aspects of sustainability would be invalid.

For a technology to be technically sustainable it needs to be efficient (limited resource use and waste production), robust (able to withstand shock loads and extreme conditions), flexible and adaptable, easy to monitor, perform at or close to its optimum for extended periods and the flow of materials through the system must be balanced. In addition, there must be sufficient resources (spare parts and technical expertise) for maintaining the technology in the area

where it is to be used. Each of these criteria could constitute potential barriers to implementation of the IWBF at the nine sample STWs and are discussed below.

4.3.1.1. Performance assessment

The performance of the IWBF was defined as the ability of the various stages and the integrated system as a whole to meet the desired outputs for which they were originally designed. However, as the proposed system is still at the conceptual stage, performance could not be assessed using primary data. Instead, the performance of the IWBF was assessed indirectly based on the ability of individual process units to melt the desired objectives. As this assessment step was based on reported performance data found in the literature, care had to be taken to ensure data used was obtained under similar environmental and operating conditions as expected at the nine sample sites. Where this was not possible, caution had to be exercised when making predictions as to the sustainability at the sample sites.

Pathogen and nutrient removal

As discussed in Chapter 3, it was intended that pathogen removal be effected in both the HRAP and the composting stage. Algal-based systems have been shown to be successful in the removal of pathogens from effluent streams. Araki *et al*. (2000) noted a 40-60% reduction in the viability of nematode eggs in the HRAP as a result of elevated pH and UV from solar radiation while Costa *et al*. (1999) recorded less than 23 faecal coliforms/100ml in final effluent from a similar HRAP treating swine wastes.

Research carried out by Shuval *et al*. (1986) pointed out that during composting of sludge heat treatment at 55^{o}-60^{o}C for several hours will ensure a total pathogen inactivation, including the most resistant helminth eggs. Furthermore, Mitchell (1978) in his laboratory-scale experiment demonstrated that there was a marked reduction in populations of the pathogenic *Salmonella enteriditis*, *Escherichia coli* and other enterobacteriaceae during vermicomposting of aerobic sewage sludge by the worm species *E.foetida*.

With regards to nutrient removal, as previously indicated in Chapter 3 (Section 3.3.2.1), Rose *et al*. (1996) reported that the HRAP reduced levels of ammonia by 75% and nitrate and phosphates by 20% and this improved municipal effluent significantly allowing it to meet

general requirements as outlined by DWAF. They also found that the AST removed additional solids, COD and coliforms from polished effluent. Garcia *et al*. (2002a) also noted a 51.9% and 25% removal of ammonia and nitrate respectively in a HRAP. As the study by Rose *et al*. (1996) was conducted within 100km of all nine study sites, it was likely that the HRAP would function equally well at these sites.

Based on the above, data from literature indicate that the proposed technology train would be highly effective for removing pathogens and nutrients from both the liquid and solid waste streams. However a number of factors, including climate, can affect the pathogen and nutrient removal capacity of the process units and needed to be considered in the context of the study sites. Previous research (Chen *et al*., 2003) has shown that both pathogen and nutrient removal within the HRAP is reduced in winter, but that this can be overcome by extending the hydraulic retention time (HRT) within the ponds (Rose *et al*., 1996). The implications are that the HRAP units would need to be of sufficient capacity to allow for the necessary HRT (probably 5 days) in winter. As such, it could be expected that both pathogen and nutrient removal in the summer months would exceed the minimum required levels.

Heavy metal removal

According to Edwards (1998), *E.foetida* has the ability to accumulate heavy metals in sewage sludge compost and when Shahmansouri *et al*. (2005) studied removal of metals from sewage sludge it was found that the heavy metal content at the end of the process was lower than in the initial materials and lower than the limits of the US EPA. However, South African heavy metal limits for agricultural use are stricter than US EPA limits. Therefore, while there is evidence to suggest that earthworms are able to remove at least a certain proportion of heavy metals from sludge, it is uncertain as to whether removal is sufficient to allow for agricultural application of the vermicast.

However, as indicated in Chapter 2 of this thesis, after conventional treatment the heavy metal levels present in sludge from the eight of the nine sample sites were lower than the set limits for South Africa, therefore the ability of earthworms to remove them was not considered important in the current context. In this case, the important issue would be that the worms might be able to ingest or assimilate the remaining metals and that these would then be

incorporated into the fish (Donaldson, 1990). This confirmed the proposal that fish cultivated on worms from the nine sample STWs should only be ornamental rather than for human consumption. Importantly, for STWs with high concentrations of heavy metals within the sludge e.g. mercury at the Driftsands STW, the potential market for vermicast might be limited, and the sludge may need to be regarded as hazardous and disposed of accordingly.

Process failure

Despite the relative simplicity of many of the processes, common causes of process failure had to be considered to determine whether any would be likely to occur if the IWBF was established at any of the nine sample STWs. Table 4.2 indicates each of the key process units and potential causes of reduction in performance. Presented in the same table are some of the potential preventative measures that can be employed to avoid sub-optimal performance of the process units of the IWBF.

One of the potential problems highlighted in Table 4.2 was the predation of worms and koi by birds. Preventative measures to avoid this are particularly important at STWs located near and/or who have bird sanctuaries on-site where opportunistic bird species such as gulls and starlings were observed (Cape Receife, Kwanobuhle, Driftsands, Despatch and the Belmont River Valley STWs) during the environmental risk assessment exercise. With regards to fish disease, in the Eastern Cape Province the risk is generally low and koi are no more susceptible to disease than other fish (Jones pers. comm., 2005). However it would be important to look for changes in behaviour of koi such as flashing, not eating, clamped fins, heavy respiration, self-isolation, gasping at the surface of the water inlet, loss of equilibrium and jumping which all indicate the need for further inspection (Passino, 1981; Pickering, 1981; Donaldson *et al*., 1984; Adams, 1990; Maule & Schreck, 1990). With a favourable climate and large number of aquaculture specialists within 100km of all proposed sites, the threats to the efficiency of the aquaculture process unit were regarded as low.

The potential problems that might arise in the HRAP and the composting process units (Table 4.2) apply equally to all nine sample STWs. Apart from the preventative measures listed in Table 4.2, the ability of the IWBF to perform optimally will also be dependant on factors such as its ability to withstand shocks and site security. Each of these is discussed below.

Table 4.2: Potential causes of reduction in performance of the proposed IWBF

Process Unit	Problem	Result	Prevention
Composting	Hotspot formation	Release of dioxins; sub-optimal degradation	Temperature must not exceed 425^{o}C
	Insufficient moisture	Inability to kill off pathogens particularly in winter months; affects duration of sludge stabilisation stage (if too dry process slows down)	Keep material at the right temperature, use water from HRAP if material becomes too dry
Vermicomposting	Fluctuations in pH, lack of oxygen, presence of toxic chemicals	Death of worms; reduced rate of vermicomposting or none at all	Regular monitoring and maintain 'ideal conditions' in units
	Predation of worms by birds	Loss of worms; reduced rate of vermicomposting	Cover units with shade cloth
HRAP	Reduced algal biomass yield rates in winter	Reduced source of additional revenue that could be obtained from sell of algae	Increase HRT in the HRAP during winter
Aquaculture	Disease causing organisms	Death of koi; reduced source of revenue; increased treatment and replacement costs	Frequent water monitoring and proper management e.g. inspection of koi
	Predation by birds and other animals	Death/Loss of fish	Provision of bird netting and fencing over and around koi ponds

Process robustness

It was recognised that biological waste treatment systems may be challenged by variations in inputs, including the inclusion of toxins, and operational conditions (temperature, moisture content, volumetric loading etc). Therefore, the key challenge to any system is to maintain performance or to recover quickly after experiencing these shocks i.e. be resilient. As discussed previously, the ability of the HRAP to remove the desired quantity of pathogens and nutrients is highly dependent on the HRT. Therefore, any significant increases in volumetric loading, which would decrease the HRT, could have significant negative impacts on the quality of the final effluent. While the current influent volumes of the nine sample STWs were known, it would be essential that the HRAPs be designed to allow for some buffering capacity in terms of flow rate. Significant permanent increases in volumetric loading would necessitate the addition of HRAP units, but would not pose a significant problem.

While variations in the quality of sewage sludge could be expected, these were likely to be small and would not pose any threat to the operation. The introduction of potential toxins to the system, particularly at those facilities that receive industrial effluent (Fish Water Flats, Driftsands, Cape Receife, Kelvin Jones) was regarded as a significant concern. Any process change or construction of new industry within the catchment of a STW could result in the introduction of toxic compounds, which could potentially retard the polishing of effluent as well as the composting and aquaculture stages. Due to the dilution effect, a significant quantity of toxic compounds need to be released and process changes or toxic discharges of a sufficiently large magnitude should be relatively easily detected and controlled by local authorities. Thus, while the impact of toxic compounds could be problematic, it would be primarily associated with STWs in larger metropolitan areas and could be controlled.

Security

The loss of a pump or other vital equipment could disrupt the entire integrated system, resulting in loss of revenue and increased environmental and health risks. Eight of the nine sample STWs were located near poorer informal communities and therefore security at these particular IWBFs was considered essential. During the site visits (Chapter 2) it was evident that access to at least three of the nine sample STWs (Cradock, Kwanobuhle, Belmont River Valley) was not controlled. Therefore, security at all but the largest of the nine sample STWs

(Fish Water Flats) was regarded as insufficient and would be particularly vital for the aquaculture process unit where high-value fish would be grown. Theft of this main income generating product would have significant implications for the economic viability of the system. Currently, this aspect is regarded as a significant threat to the viability of the proposed IWBF and would need to be addressed prior to construction of the units.

4.3.1.2. Product analysis

The basis for sizing of the individual process units would be the expected quantity of material to be treated (water and sewage sludge) and this would determine the quantity of each product generated. Therefore the aim of the product analysis was to determine:

- The type and maximum quantity of final products produced e.g. would all the worms from the vermicomposting process unit be used up as koi feed in the aquaculture process unit or would some be available for sale;
- Whether the above would be influenced by the location of the IWBF;
- The theoretical maximum amount of treated effluent and sludge that could be polished and stabilised respectively, based on factors such as land availability;
- Determine which of the process units was considered rate-limiting in terms of overall production.

All calculations were based on a facility receiving 1ML of municipal wastewater per day. When determining the product quantity, the current study assumed that similar conversion rates as reported in the literature (Figure 4.2) could be achieved.

Assuming high-flow through 1ML/day pond designs, it was calculated that the volume of polished water available was insufficient to support the theoretical maximum quantity of koi based on the amount of feed (worms) available from the vermicomposting process unit of a 1ML/day facility. However, if one adopted an intermediate system between full flow-through and a stagnant pond, the availability of worm biomass (feed) would be the limiting factor. Therefore, from the product analysis perspective, STWs would have to base the number of koi grown in the aquaculture facility not on the amount of polished water available from the HRAP but on the number of worms available from their vermicomposting unit.

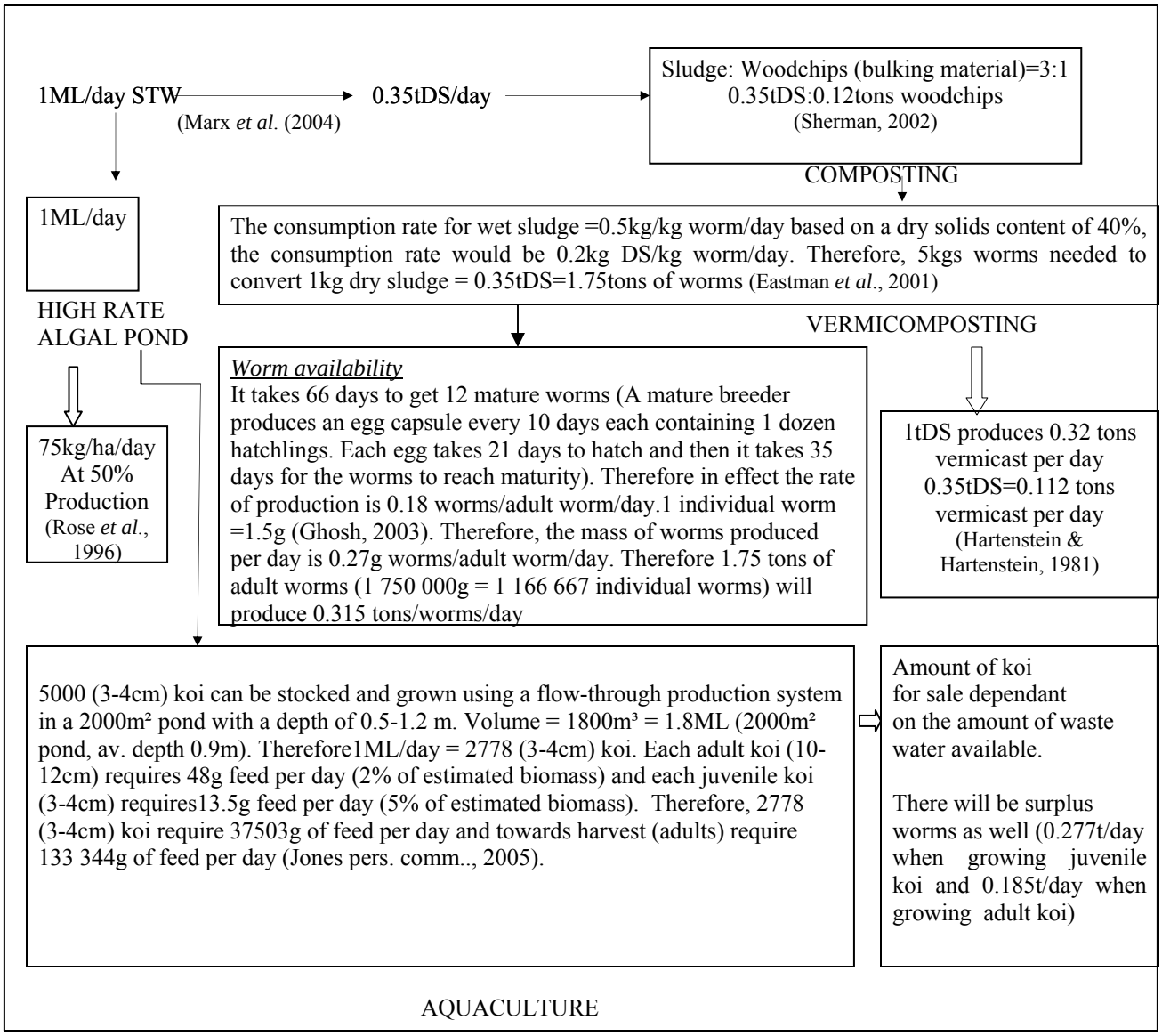

Figure 4.2: Materials flow balance and product formation for a 1ML/day IWBF

Since the total initial worm population in the vermicomposting unit will be the actual amount required to convert all the sludge, none of these worms would be available as feed. Therefore, extra worms will only be available once the original worms have reproduced. As a result, for 66 days (Figure 4.2) after the start-up period, all water polished in the HRAP will most likely be discharged directly until sufficient worm biomass is available to support the aquaculture process unit.

Based on the results of the product analysis for a 1ML/day facility above, the potential inputs and outputs at each of the nine sample STWs of varying capacities were calculated and the results of these calculations are indicated in Table 4.3.

Table 4.3: Materials balance: Estimated inputs and outputs of the IWBF at nine sample STWs in the Eastern Cape Province

STW	Waste water treated (ML/day)	Inputs			Outputs									
		Sludge generated (tDS/day)	Bulking material required (tons/day)	Worms required (tons/day)	Vermicast produced (tons/day)	Algae from HRAP (t/day)	Worms produced per day (tons)	Number of koi that can be supported			Food required based on wastewater koi number (tons)		Surplus food (tons)	
								Based on availability of feed		Based on wastewater				
								Juveniles	Adults		juveniles	Adults	When growing juveniles	When growing Adults
A	112.0	39.2	13.0	196	12.5	5.6	35.28	2613296	735056	311024	4	15	31.28	20.28
B	7.5	2.6	0.9	13	0.8	0.3	2.34	173331	48754	20828	0.28	0.9	2.06	1.44
C	12.0	4.2	1.4	21	1.3	0.6	3.78	279996	78756	33324	0.45	1.59	3.33	2.19
D	22.0	7.7	2.6	38.5	2.4	1.1	6.93	513326	144386	61094	0.82	2.9	6.11	4.03
E	7.8	2.7	0.9	13.5	0.8	0.3	2.43	179997	50629	21661	0.29	1.04	2.14	1.39
F	4.6	1.6	0.5	8	0.5	0.2	1.44	106665	30002	12774	0.17	0.6	1.27	0.84
G	5.1	1.7	0.6	8.5	0.5	0.2	1.53	113332	31877	14163	0.19	0.7	1.34	0.83
H	3.0	1.0	0.4	5	0.3	0.1	0.9	666666	18751	8331	0.11	0.39	0.79	0.51
I	4.8	1.6	0.6	8	0.5	0.2	1.44	106665	30002	13329	0.18	0.6	1.26	0.84

KEY: A=Fish Water Flats, B=Driftsands, C=Cape Receife, D=Kelvin Jones, E=Kwanobuhle, F=Despatch, G=Belmont River Valley, H=Graaff Reinet, I=Cradock

It is clear from the Table 4.3 that the estimated outputs (products) of the IWBF are proportional to the magnitude of the inputs (water and sludge). For example, Fish Water Flats generates 39.2tDS/day from conventional wastewater treatment and would be able to produce 12.5tons of vermicast per day if all this sludge was composted and vermicomposted. Smaller STWs such as Graaff Reinet would be able to generate only 0.3 tons of vermicast per day since they only produce 1.1tDS/day from conventional treatment. It is also evident that there was no theoretical maximum amount of 'treated' effluent and sludge that could be polished and stabilised respectively because all the key units of the process are modular. The IWBF can therefore be constructed to meet flows from any size STWs depending on the availability of land surface area for the process units. The size of the koi ponds at a particular facility will depend on the number of fish being reared which, in turn, will depend on the quantity of water, the limiting factor that will also affect how many worms are left over for sell.

From the discussion above, it is clear that the materials flow analysis was useful in that it allowed for the detection of those elements of the IWBF that could limit performance and indicated the aspect of the IWBF that was most vital (i.e. if performs sub-standardly, will have the greatest negative impact on the rest of the process). Worm availability from vermicomposting was considered as a key factor as it would affect the rate of conversion in the vermicomposting process unit, the availability of koi feed, the amount of koi that could be reared and the amount of money that could be raised from the sale of products. Additional worms could have been sold as live bait or as inputs to other vermicomposting centres. All algal biomass could be sold either as fertiliser or cattle feed. The most 'valuable' product of the system was the koi and the quantity produced would have important implications for the financial sustainability of the operation as will be addressed in more detail at a later stage.

Therefore since the HRAP (water quality) and vermicomposting units would have the greatest knock on effect in the IWBF they would need to be well managed and closely monitored at all STWs.

4.3.1.3. Process efficiency

In order to reduce operational costs, the initial design of the IWBF incorporated process units with low energy requirements under optimum conditions. Energetic inputs are limited to the

paddle wheel of the HRAP. The energy requirements for the paddle wheel of the HRAP are exceptionally low (0.335kW/ML) (Rhodes University Environmental Biotechnology Group, 1997). However, alternative methods of powering the paddle wheel are possible. Paddle wheels can be driven using compressed air instead of electricity although initial set up costs would be relatively expensive (Rose *et al*., 2000). Similarly solar panels may be used to drive the paddle wheel but require a high initial capital outlay (Rose *et al*., 1996). Alternative energy supplies such as windmills have been used with some success at biofilter treatment works (Hoza pers. comm., 2002), but solar power has yet to be used in this context. Another potentially suitable alternative option that needs to be investigated further for all sample STWs except Fish Water Flats (which already uses this alternative) is the recovery and utilization of methane presently wasted to the atmosphere. Using methane as an energy source has the potential to significantly reduce the energy demands of the IWBF and wastewater treatment. This is not a new undertaking and according to Oswald (1995), the methane content of the biogas released from anaerobic digesters has already been used successfully in the generation of electricity at various wastewater treatment plants around the world.

Although aquaculture operations require large quantities of energy (Jones pers. comm., 2005), the topography at most of the sample sites and the choice of pond production system i.e. flow-through, would minimise the energy requirements. At all nine sample STWs it would be possible to design the system in such a way to allow for gravity feed of water from one ponding unit to the next, thereby reducing the reliance on pumps and minimising energy demands.

Waste of any sort (liquid, solid, gas, heat, noise) from the system would be negligible and the only potential sources would be limited heat loss from the paddle wheel motor. All other inputs to the system, including fish food and faeces, would be used to generate the final product.

4.3.1.4. Accessibility of technical expertise and component parts

Potential users of technologies must have access to "servicing resources" and component parts in order to avoid premature termination of these technologies' service lives. According to Dunmade (2002), "servicing resources" include technical experts, maintenance facilities

and materials specific to the technology needing repair. It is accepted that most process units involving piping and machinery, such as the HRAP and aquaculture facility, would require adequate maintenance to ensure optimal and sustained performance. Due to wear and tear or breakdown, parts fail and need replacement. When this happens, unless replacement parts are accessible, the service life of the equipment will end abruptly. In the IWBF, the most likely parts requiring replacement are those of a mechanical nature such as the paddle wheels of the HRAPs and pumps. Other components such as the aeration tanks in the koi ponds are also particularly susceptible. Local availability of parts is essential for maximising the service life of the system and reducing the 'down time' of one or more process units (Dunmade, 2002). The availability of replacement parts is likely to be influenced by distance from supply centres, primarily larger metropolitan cities.

Of the nine sample STWs, Fish Water Flats, Kelvin Jones, Driftsands and Cape Receife are not likely to experience problems related to the availability of spare parts and technical expertise due to their close proximity (less than 50km) to the city of Port Elizabeth the largest city in the Eastern Cape. These STWs are linked to transport networks and surrounded by the manufacturers and suppliers of spare parts and consumables, including oxygen cylinders for the aquaculture process unit. However, STWs located in smaller, more distant towns (>150km) from metropolitan areas (Belmont River Valley in Grahamstown, Graaff Reinet, Cradock) are likely to face delays of up to one week in the case of severe mechanical failure. Although the environmental and economic impacts of a lengthy down-time could be severe, the risk associated with the availability of spare parts can be minimised by maintaining a suitable supply of spare parts (motors, pumps etc.) on-site and implementing a sound maintenance regime. Additionally, components of a non-mechanical nature including the worm species used in the vermiculture process unit need to be readily available. Although *E.foetida* is a European worm species foreign to South Africa, a supply is readily available in the Eastern Cape.

With a system such as the IWBF, there is also a risk of biological failure. If warning signs of failure are detected at a sufficiently early stage, the advice of an experienced expert may be vital to prevent complete failure of any of the biological units (composting, vermicomposting, aquaculture and the HRAP). The availability of technical experts to solve these potentially

complex biological problems might be problematic although all nine sample STWs were situated within 100kms of universities where expert assistance could be obtained. However, before establishing the IWBF at more remote sites, it would be necessary to ensure that suitably qualified personnel were available to assist in the case of process failure. This 'help' should ideally be onsite but a certain degree of assistance can be provided remotely. In relation to other aspects, it is unlikely that maintenance will be a problem at any of the nine sample STWs because none of the IWBF's process units employ highly sophisticated equipment and the skills necessary to maintain and repair the equipment are readily available throughout the Province.

Based on the assessment of the technical sustainability of the IWBF, it appeared that site security was the single biggest threat to the success of the process. Although other aspects (climatic conditions, predations, mechanical failure etc.) posed a potentially significant threat at some of the nine proposed sites, the risks could be reduced significantly with good planning, proper management and maintenance. Therefore, this TA found that technical aspects were not expected to pose a barrier to implementation of the system particularly if proper arrangements are made by STWs and municipalities prior to procurement.

4.3.2. Social sustainability

The prime objectives of designing the IWBF were to improve sewage sludge management and sewage treatment and, in so doing, protect human health and the environment. However, no matter how good a technology may be in terms of its potential to achieve the objectives for which it was designed, social factors will have a significant influence on its sustainability within a particular society. According to Dunmade (2002), "*…a number of technologies have been introduced in developing countries which ultimately failed for social reasons*". Therefore, one must take into account the fact that society is dynamic in nature and as a result, the effects of current and future social changes must be adequately considered at the planning stage, so that money spent on developing or procuring a technology may not be eventually wasted (Dunmade, 2002). The social factors that were considered during the assessment of the IWBF were public acceptability (social and cultural influences of the technology, levels awareness), job creation and capacity building, health, health related legal requirements (Table 4.1).

4.3.2.1. Public awareness and acceptability

According to Marx *et al*. (2004), "*It does not make sense to implement a technology that is in direct conflict with any local needs or issues. On the contrary, the technology to be implemented must be modified to such an extent that all the potential local issues are resolved or adequately addressed*". Additionally, the level of awareness of potential users of the IWBF is important since awareness influences acceptance. The IWBF is a novel system; therefore, public awareness is currently non-existent. However, the process units (vermicomposting, composting, HRAP, aquaculture) are all well-known in developing countries (Cross & Strauss, 1985; Shuval *et al*., 1986; Edwards, 1988; Phillips, 1988; Raymond *et al*., 1988; Harris *et al*., 1990; Logsdon, 1994; Edwards & Bohlen, 1996; Edwards, 1998; Dominguez *et al*., 1997; Sherman, 2002; Marx *et al.,* 2004) and there is sufficient evidence to indicate that the technologies are readily accepted by the majority of communities (Strauss & Blumenthal, 1989; Israeli & Kimmel, 1996; Edwards, 1998; Ndegwa *et al*., 2001). Nevertheless, there are still some factors that could affect public acceptability of the proposed IWBF at the nine sample sites and these are discussed below.

Cultural attitudes regarding the handling of wastes could affect the sustainability of the proposed IWBF. For example, in some societies the handling of human wastes is 'taboo' (Strauss & Blumenthal, 1990) and this could potentially affect labour availability. However, with regards to the nine sample STWs, the latter should not pose a problem as the potential pool of the employees at the various sites were Xhosa, a tribal group who apparently have no cultural objection to the handling of waste material (Macontywa pers. comm., 2005). Thus, cultural objections to the development of the IWBF were considered unimportant in the current context, but would need to be investigated at other sites.

The potential for offensive odours could also present a significant obstacle to implementing technologies that involve storage and degradation of sewage sludge. Not only do the odours themselves cause a public concern, but odours also trigger fears that 'foul-smelling' residues from the IWBF must be toxic and harmful. Of the nine sample STWs, odour was considered particularly important for STWs such as Kwanobuhle, Graaff Reinet, and Cradock that are located 500m, 1km and 1km, respectively, from the nearest surrounding residential communities. However, apart from current complaints of odour (Mancotywa pers. comm.,

2005), the importance of removing sludge from their 'back-yards' might be considered more significant. Proper construction of the IWBF (particularly the ponds) e.g. taking wind direction into account and good management practices should be able to minimise most odour problems reducing the significance of this concern, although occasionally even the best run facilities may emit odours.

Concerns have also been raised about the possible health effects associated with inhalation of airborne dust ("bioaerosols") originating from one of the IWBF's process units-composting. According to Millner *et al*. (1994) bioaerosols (e.g. *Aspergillus fumigatus*) from composting do not impose any unique endangerment to the health and welfare of the general public. However, they acknowledge the need for further research into the occupational hazards to workers at composting sites as a result of "bioaerosols".

Public acceptability of the IWBF itself is important as is acceptability of the products that would be generated since the economic viability of the IWBF (Section 4.3.4) will be reliant on the presence of a market for the various products. The use of products including algae for stock feed have the potential to relieve the pressure on the soya bean industry for stock feed, freeing up more food for human consumption (Chowdury *et al*., 1995). However, there continues to be some public resistance to the beneficial use of sludge, based primarily on concerns about potential health, environmental, or nuisance impacts (odours, flies etc), and according to the US EPA (2004), "*although public perception is often not based on science and can be irrespective of the degree of risk to human health and the environment, it can present a significant deterrent to increased beneficial use of sludge*". Therefore, it was important during this technology assessment to ascertain and understand the concerns of the public particularly of potential users of the products generated by the IWBF. As stated earlier, this was achieved by means of a questionnaire survey, the details of which were provided in Section 4.2 and Appendix II.

The results of the questionnaire survey indicated that 80% of the farmers (n=20) and 85% of the plant nurseries (n=20) that took part in the survey were willing to make use of vermicast. However, all respondents expressed concerns about the potential dangers to human health as a result of growing plants using a sludge-based fertiliser, and, as a result emphasised their need

for extensive information about the potential dangers of this fertiliser. This concern entrenched not only the potential users' but the public's need to have access to such information and for scholars, academic institutions, municipalities, STWs and governments to make this information readily available.

4.3.2.2. Job creation and education through training

Recent protests etc. indicate that service delivery is high on the agenda of poor communities in the Eastern Cape Province of South Africa but the IWBF does not really address this issue. It will however, address the issue of job creation and should therefore be acceptable. At present, the sludge disposal techniques employed at three of the nine sample STWs in the Eastern Cape do not require a large labour force because sludge is disposed of either by pipeline (Kwanobuhle, Kelvin Jones) or by truck (Fish Water Flats). However, as all nine sample STWs were located close to poorer communities where the incidence of unemployment is estimated to be as high as 45.3% (Department of Labour, 2005), the creation of any additional employment opportunities would be of significant local and regional benefit.

The design and construction phases of the IWBF would most likely be outsourced with design and commissioning managed by highly-skilled (possess at least a tertiary education) individuals, although others with a range of skills would be employed on a temporary basis during construction. As a result, the construction phase would most likely benefit local communities although for a limited time period (probably 6-8 months).

Table 4.4 indicates the estimated number of jobs according to different skills levels required during the operational phase at a single 1ML/day IWBF. The IWBF would probably have at least two permanently employed skilled individuals (Table 4.4) with one responsible for the composting and vermicomposting units and the other to oversee the ponds (HRAP, aquaculture). In addition, as emphasised in Section 4.3.1.4, all process units must have at least one temporary highly-skilled individual or expert on the individual process unit readily available should any breakdown occur and the problem is of such a nature that it is not easily solved by the senior permanent staff. The vermicomposting and aquaculture process units also require some permanent semi-skilled/unskilled (possess at least a primary education) labour primarily for harvesting the products from the system, particularly from vermicomposting and

aquaculture.

Table 4.4: The estimated number of employees according to skills levels required for each of the 1ML/day IWBF's process units during operation

Level of skill	Duration of employment	Process unit				Total
		HRAP	Composting	Vermicomposting	Aquaculture	
Highly skilled	Permanent					-
	Temporary	1	1	1	1	4
Skilled	Permanent	0.5	0.5	0.5	0.5	2
	Temporary					-
Semi-skilled or Unskilled	Permanent	1	2	3	4	10
	Temporary					-

Based on the above, the development of even a small 1ML/day IWBF would create much needed employment for sixteen individuals with at least twelve permanent jobs being created at each site. As indicated in Table 2.2 (Chapter 2, Section 2.2.2) all of the nine sample STWs had a capacity greater than 1ML/day and thus would more than likely require additional permanent employees. The above analysis did not examine the number of indirect jobs created through the processing and sale of the various products of the system, which would be of further benefit to local communities. Nevertheless, from the perspective of job creation, development of the IWBF appeared highly favourable.

In addition to job creation, individuals employed at the STWs, particularly in the sludge management operation, could be trained to perform a range of tasks required for successful operation of the proposed IWBF. This would not only result in capacity building but in an increase in social capital as well because these are skills that workers would be able to maintain.

4.3.2.3. Health

Potentially harmful unprocessed sewage sludge would still be stored on site, at least temporarily, prior to composting, and during this period could pose a health threat to employees and, potentially nearby communities. For this and other reasons stated in Section 4.3.1.1, access to the STWs would need to be tightly controlled and certain minimum security measures put in place. In order to reduce the health threats to employees the necessary precautions including health and safety training, the wearing of protective clothing and inoculation against certain diseases would need to be enforced. Health risks are bound to be higher at STWs treating industrial waste (Fish Water Flats, Driftsands, Cape Receife and Kelvin Jones) due to the potential presence of toxic compounds such as the mercury found in the 'treated' sludge of Driftsands STW. The issue of health is discussed further below.

4.3.2.4. Health related legal requirements

South Africa's Health Act 63 of 1977 and the Occupational Health and Safety Act 85 of 1993 stipulate a number of conditions that will influence the suitability of the IWBF. The Health Act outlines the requirements for general hygiene at waste treatment plants mainly because effluent treatment and solid waste disposal result in employee's exposure to potentially unhygienic conditions. The Occupational Health and Safety Act 85 of 1993, applicable at any wastewater treatment facility, regulates health and safety in the work place, including the handling of machinery and waste. This Act specifies that proper management elements to reduce workers' exposure to the harmful agents contained in sewage and sludge must be put in place. According to Mancotywa pers. comm. (2005), such elements are currently in place although during the site visits it was evident that employees were not wearing any personal protective equipment at any of the nine sample sites.

In order to comply with the requirements of the Occupational Health and Safety Act, appropriate personal protective equipment such as goggles, gloves, splash-proof face shields, nose masks and liquid repellent overalls must be provided and worn at all times for all job duties likely to result in exposure to these agents. In addition, more emphasis must be placed on monitoring the inputs and outputs of the IWBF and management of the site as well as maintenance and mechanical failure. Emergency procedures are equally of critical importance at all sample STWs. Provided that the above are adhered to, the proposed system would not

result in the contravention of the above mentioned health-related legislation in South Africa. However, due to high summer temperatures at all nine sample sites (mean 28^{o}C), employees would possibly be tempted to work without the necessary additional clothing unless an effective educational and management system was in place to warn them as to the dangers of this.

The assessment of social sustainability of the IWBF determined that there did not appear to be any social barriers to implementation of the IWBF except for the likely controversy surrounding the use of vermicast a sludge-based fertiliser for growing plants. The biggest social advantages of the IWBF appeared to be the reduction of health risks and nuisances (flies, odours) and the creation of direct and indirect employment. Cultural sensitivities and community acceptability would, however, need to be investigated at all potential sites.

4.3.3. Environmental sustainability

Although the conceptual design of the IWBF would, in theory, reduce many of the environmental threats currently associated with STWs in the Eastern Cape, it may be associated with other negative environmental impacts. Therefore, in order to determine the long-term environmental sustainability of the proposed IWBF, it was necessary to assess the potential impacts using a range of appropriate criteria. These fell into two broad categories namely "resource demands" and "environment-related legal requirements". Each of these is discussed in detail in Sections 4.3.3.1 and 4.3.3.2 below.

4.3.3.1. Resource demands

Due to the nature of the technologies in the IWBF process stream, it was expected that the resource demands would be low as was indicated in Section 4.3.1.3. However, the demands on resources such as land, energy, and chemical inputs of the system required further analysis. Although water and energy are recognised as important resources, they were excluded from this analysis as all water demands of the system could be met by the use of polished effluent and energy efficiency was covered in Section 4.3.1.3.

All the process units of the IWBF have relatively large land requirements, particularly the vermicomposting and aquaculture stages (Chapter 3, Section 3.3.2.1). The estimated land

requirement for a single 1ML/day IWBF was 3382.2m^2 (0.34ha) based on surface area requirements of 1000m^2 for two HRAPs, 6m^2 for two ASPs, 40m^2 for drying beds (Rose *et al*., 2002), 1111.2m^2 for the aquaculture process unit-2000m^2 used to grow 5000 koi (Jones pers. comm., 2005), 1084m^2 for the vermicomposting unit (Ndegwa & Thompson, 2001; Sherman, 2002) and 141m^2 for the composting unit (Dominguez *et al*., 1997; Ndegwa & Thompson, 2001). Based on the land requirements of a 1ML/day facility, it was possible to determine that of other size facilities e.g. a 2ML/day facility will have land requirements that are twice that of a 1ML/day facility.

Table 4.5 provides a comparison of the estimated land requirements based on a series of literature resources (Dominguez *et al*., 1997; Ndegwa & Thompson, 2001; Jones pers. comm., 2005; Rose *et al*., 1996; Sherman, 2002) for establishment of the IWBF at each of the nine sample STWs (using their daily flow rate) and the estimated area of vacant land currently available at each site. The latter was calculated using Google Earth (www.google.com, 2005) combined with estimates obtained during site visits.

The nine sample STWs had different amounts of vacant land available to them depending on where they were located. The area of un-used land at the two largest STWs, Fish Water Flats and Kelvin Jones was regarded as insufficient for the establishment of an IWBF to process all of the sludge produced. The STWs at Belmont River Valley, Driftsands, and Cape Receife were considered to have sufficient land for the establishment of an appropriately sized IWBF. Although the remaining STWs (Graaff Reinet, Despatch, Kwanobuhle and Cradock) had a sufficient area of land available to them, while in the past buffer zones were required around STWs, today this "free" land has been taken over by informal housing which is sometimes built up to the boundary fence of STWs. Therefore, at these STWs, people may have to be relocated to make enough land available for construction of the IWBF.

Removal of people will have important implications particularly for social sustainability. Even if people were resettled elsewhere there are still inherent complexities associated with this. According to De Wet (1995), involuntary removals and resettlements involve imposed spatial change (people have to move from one settlement and area to another) with people finding themselves in larger and more heterogeneous settlements which will have cultural,

Table 4.5: Land requirements and surrounding land use type at nine sample STWs in the Eastern Cape Province.

Name of STW	Surrounding land use	Estimated amount of land required for IWBF based on daily flow rate (m^2)	Estimated amount of land available to STW (m^2)
Fish Water Flats	**Industry**	**378 806.4**	**6500**
Driftsands	Commonage	25 366.5	130 000
Cape Receife	Nature reserve	40586.4	104 000
Kelvin Jones	**Industry**	**74 408.4**	**13 000**
Kwanobuhle	Residential	26 381.16	78 000
Despatch	Residential	15 558.12	52 000
Belmont River Valley	Agricultural settlement	17 249.22	90 000
Graaff Reinet	Commonage, Residential	10 146.6	39 000
Cradock	Commonage	16 234.56	48 000

social, political and economic implications. Resettlement also requires people to develop new sets of relationships and they may experience serious social disruption or 'dislocation' depending on the speed and degree with which removal takes place (Cernea, 2000). Resettlement of people may also result in a change in patterns of people's access to resources with some located further from sources of work and shops resulting in additional costs of transport and higher prices (Koenig, 2001). This is a very sensitive issue that could represent a potential barrier to implementation of the IWBF at the aforementioned STWs.

Energy requirements

Energy requirements need to be considered not only due to their environmental effects but technical and economic aspects as well. Energy requirements have been discussed extensively in Section 4.3.1.3. However positive environmental impacts such as reduced resource use due to the suggested use of methane and solar energy and reduced contributions to greenhouse gases resulting from methane collection which have not been previously discussed might also

be realised. It is important to note however, that the energy associated with the transportation of raw products, an economic consideration, has not been considered here since it is outside the scope of this study.

Waste generation and disposal

The proposed IWBF is essentially a closed system and will not be generating any waste for disposal into the environment.

4.3.3.2. Environment-related legal requirements

In South Africa a number of Acts are relevant to the operations of STWs and solid waste (sludge) management. The broader requirements of these Acts together with economic and social considerations were used to identify the key performance criteria and guide the design of the IWBF. The purpose of the current discussion was to identify any aspects of the final design of the IWBF that had the potential to contravene local environmental legislation, in order for possible mitigation or avoidance measures to be proposed.

Water quality

The water needed in composting municipal sewage sludge has the ability to form leachate which could contain an array of elements and chemicals that were originally in the compost material (Dominguez *et al*., 1997). The formation of leachate from temporary sludge storage areas and the compost heaps poses a pollution threat to ground and surface water resources. The probability of contaminants from sludge contaminating nearby water resources was investigated prior to the development of the IWBF as discussed in Chapter 2 (Section 2.3.2). In this part of the study, components such as heavy metals present in sewage sludge were shown to leach into surrounding surface water resources which is in contravention of the National Water Act, National Environmental Management Act (NEMA), and potentially Section 24 of the Constitution (Glazewsky, 2000).

The Constitution Act 108 of 1996 of the Republic of South Africa entitles South Africans to expect that their environment will be protected from unsustainable use and harmful impacts. The Bill of Rights (Chapter 2 of the Constitution) contains a number of rights relevant to natural resource management, to the extent that "*an Act or particular statutory provision that does not uphold these rights is unconstitutional*" (Glazewsky, 2000). The purpose of the

National Water Act 36 of 1998 is to ensure that the country's water resources are protected, used, developed and conserved in ways which take into account the protection of aquatic and associated ecosystems, address basic human needs, ensure the reduction and prevention of pollution, and meet international obligations. Sections 19, 20, 21 and 22 are particularly relevant to pollution control. Section 19 deals with the prevention and remedying effects of pollution. Section 20 deals with the control of emergency incidents and states that, "*The person who owns, controls, occupies or uses the land in question is responsible for taking all reasonable measures to prevent any pollution of a water resource from occurring, continuing or recurring. If these measures are not taken, the catchment management agency concerned may itself do whatever is necessary to prevent the pollution or remedy its effects, and to recover all reasonable costs from the persons responsible for the pollution*". However, it is possible for the user to be exempted from these provisions, subject to the conditions that the minister may impose. Section 21, requires that "*water used for industrial purposes be purified in accordance with gazetted standards and returned to the point from which it was abstracted"*. Section 22 empowers the Minister to direct that a person who has control over land take steps to prevent water pollution (DEAT, 2000). The control of fresh water pollution is governed by thirty-one pieces of national legislation, at least three provincial ordinances and by countless by-laws (DEAT, 2000). This NEMA (Act 107 of 1998) forms the overarching framework for environmental management in South Africa, and incorporates among others, the principles embodied in the White Paper on Integrated Pollution and Waste management (January 2000), and the National Waste Management Strategy (NWMS) (October, 1999). Section 28 of NEMA imposes a "*duty of care on every person who causes, has caused or may cause significant pollution or degradation of the environment to take reasonable measures to prevent the pollution or degradation of the environment from occurring, continuing or reoccurring*". This is known as the "polluter pays principle". Insofar as such harm to the environment is authorised by law or cannot reasonably be avoided. As the principal framework Act for environmental issues, it has direct relevance for the implementation of solid waste management strategies. Solid waste in South Africa is principally governed by the Environment Conservation Act 73 of 1989, and in particular Section 20 of the Act which deals with waste management and permitting of waste disposal sites, and indicates that "*waste can only be disposed of at a waste disposal facility that has a permit issued by the Minister of Water Affairs and Forestry*". In addition, the following

publications or procedures are also applicable and need to be consulted:

- Permissible Utilization and Disposal of Sewage Sludge (Department of Agriculture *et al*., 1997);
- Addendum No 1 to Permissible Utilization and Disposal of Sewage Sludge (1st edition) 1997;
- Water Use and Registration Management System (WARMS);
- Minimum Requirements for handling, classification and disposal of hazardous waste;
- Minimum requirements for water monitoring at waste management facilities (2nd edition) 1998 from the Department of Water Affairs and Forestry.

All of the above-mentioned legislative documents must be consulted because a preliminary consultation with geological maps revealed that all nine sample STWs were located on rock types often associated with aquifers including basalt, granite and sandstone (Truswell 1977). As such, containment of leachate would be essential at all nine sample sites. According to Sherman (2002), composting operations should ensure that sludge storage areas and composting units incorporate appropriate liners to reduce possible contamination of water resources. Any leachate should be contained and treated together with municipal wastewater. Such prevention measures are particularly important for STWs located close to fresh water resources (Belmont River Valley, Kwanobuhle) and those currently discharging effluent to the marine environment (Driftsands, Cape Receife).

In addition to the above, effluent from the aquaculture facility was likely to contain a high concentration of nutrients such as ammonia (Rose *et al*., 1996) and according to the NWA, can not be disposed of directly to a river system without treatment. This was considered during the design of the IWBF and was addressed through the inclusion of a second HRAP to remove nutrients from the aquaculture effluent stream as indicated in Figure 3.3. Based on the above, although the proposed IWBF has the potential to pollute water bodies and thereby contravene certain Acts, the risks could be minimised through correct design and operation of facilities.

Air quality

The law relating to air pollution in South Africa is in the process of being reformed in accordance with the Department of Environmental Affairs and Tourism's law reform process. The Atmospheric Pollution Prevention Act 45 of 1965 (APPA) has for many years been denounced as having inadequate compliance and enforcement mechanisms necessary to implement its provisions effectively. In addition the Act largely governs point-source emission control which does not take into consideration the cumulative impacts of air pollution in areas where the concentration of emissions of harmful substances into the atmosphere are substantial. Accordingly the APPA has been replaced by the National Environmental Management: Air Quality Act 39 of 2004 which was promulgated in February 2005 and is not yet in force. The Act controls the operation of a range of processes likely to cause air pollution (termed 'scheduled processes'), smoke pollution, and emissions of dust and fumes etc. Management of air pollution is based on regulation and licensing. Licensing of scheduled processes is based on the application of the 'best practicable means' test which places emphasis on the technology used, rather than on the air quality. The license does not confer a 'right' to pollute. However, there is currently no legal requirement for air quality monitoring in South Africa.

If all sample STWs followed the example set by Fish Water Flats STW and collected the methane generated during sludge treatment, they would not only save revenue on buying electricity but they would also be operating in accordance with the Air Quality Act.

Fertiliser quality

The use of fertilisers in South Africa is controlled under the Fertilisers, Farms Feeds, Agricultural Remedies and Stock Remedies Act 36 of 1947. This Act also regulates the importation, sale, acquisition, disposal and use of such remedies. In terms of the Act, fertilisers and farm feeds must be registered. In addition, the Conservation of Agricultural Resources Act 43 of 1983 embodies in its guidelines the prevention of any pollution that may occur through the application of sewage sludge to agricultural soil in the Permissible Utilisation and Disposal of Sewage Sludge (PUDSS) guideline document (Department of agriculture *et al*., 1997). At present the PUDSS allows the use of type D sludge on most land as long as the sludge is mixed or covered with soil whenever possible. It is also recommended

that the pH of the soil on which sludge is to be applied be greater than 6.5 because the mobility and availability of any heavy metals left in the sludge are greatly increased at pH values below 6.5. However, when growing vegetables for consumption (raw or cooked), sludge must be applied during planting. The restrictions placed on Type D sludge would potentially be the same ones placed on the use of vermicast-the fertiliser that will be generated from the IWBF, although vermicast has better qualities (more stable, consistent and less negative impact on the environment) than type D sludge. This would essentially make the project more viable.

Biodiversity

South Africa's National Biodiversity Act divides 'aliens' or organisms (plants, animals, microorganisms) which do not naturally occur in an area, and which are deliberately or accidentally introduced by humans to ecosystems outside of their natural range (Huntley *et al*., 1989), into (a) those that are problematic and harmful, in that they impact negatively on biodiversity; and (b) those that are benign and in many instances serve useful purposes. Generally, as long as organisms provide important social and economic benefits, and are not invasive causing serious ecosystem degradation, disrupting ecological processes, and resulting in species extinctions and possible reductions in genetic diversity through hybridisation, then they are acceptable (Huntley *et al*., 1989).

E.foetida, the worm species proposed for use in the vermicomposting process unit, is an 'alien' as is *Cyprinus carpio*, the species of koi that will be grown in the aquaculture process unit of the IWBF. *E.foetida* and *C.carpio* would be introduced to serve useful purposes but both these species might result in a reduction in genetic diversity through hybridisation. Vermicast will probably contain some worm eggs which will then be spread into the environment together with the fertiliser vermicast, whereas koi eggs and/or young could pass from the culture units, through the HRAP into fresh water systems. Therefore as stated in Section 65 (1) of South Africa's National Biodiversity Bill, "*A person may not carry out a restricted activity (includes agriculture) involving a specimen of an alien species without a permit which will only be issued after a prescribed assessment of risks and potential impacts on biodiversity in terms of Chapter 7*". This clause therefore requires that all STWs apply for permits in order to use these species. Koi cultivation operations all employ certain measures

to ensure that no fish escape from the facilities into local river systems and these measures would need to be included in the proposed IWBF.

Based on the results of the assessment of the environmental sustainability of the IWBF, the biggest potential threats were the production of leachate and the management of alien species, with production and release of methane being potentially important over the long-term. Inclusion of appropriate design and management procedures would reduce the threats and it is predicted that potential environmental costs would be exceeded by the environmental, social and economic benefits of the system. Despite the above, the availability of sufficient land for the IWBF was considered a significant barrier to establishment of the system at the two largest STWs, Fish Water Flats and Kelvin Jones.

4.3.4. Economic sustainability

Prior to more modern TAs which encompass a wider definition of sustainability, technologies were assessed primarily on financial and economic considerations. These still form part of the integrated TA process, especially in developing countries where funding for environmental protection is often limited. Therefore, it was necessary to ascertain the total tangible economic costs and benefits of the proposed technology in order to assess the net income it would generate. Another important factor suggested by Dunmade (2002) was that, "*consideration should not be limited only to procurement, installation and commissioning but to maintenance costs as well since several technologies have been abandoned around the world before completion because the requisite funding for installation and maintenance could not be obtained*". Criteria such as value of the products (market), potential costs (capital, operation, maintenance) and benefits (income), affordability, and location (Table 4.1) were considered as important indicators of the economic sustainability or economic barriers to the implementation of the IWBF and were subjected to further investigation.

4.3.4.1. Product value and markets

The likelihood of investing in the IWBF will be reduced if there is no market for its products or if the cost of production and transportation of products to the market exceeds their total market value. Thus it was important to determine the market value of the products relative to the capital and operational costs.

Data regarding the market value of vermicast in the Eastern Cape Province of South Africa was gathered using the same questionnaire as described in Section 4.2. The price that farmers and plant nurseries were willing to pay (R4-10/kg) was lower than the actual retail price of vermicast on the market (1kg of vermicast has a market price of R20 in South Africa). However, because vermicast is a superior product, once local users realise the benefits of this product, it is expected that the demand, and therefore the value, of the product will increase. Two important issues to consider were that marketing needed to be undertaken, and that income from the vermicast represented a small fraction of the potential total income from the system. Due to the value of the koi, the system was expected to be economically viable even if no income was received from the sale of vermicast. This aspect will be discussed in greater detail in Section 4.3.4.2.

The location of markets is also important since it determines factors such as transport, packaging and storage costs etc. of products. The questionnaire survey found that none of the respondents were currently using vermicast on their establishments. However, 80% of the farmers and 85% of the plant nurseries were willing to use of or sell vermicast. Farmers and nurseries located in cities were more willing to make use of vermicast than those in small towns although the former were adamant about the need for more information on vermicast. This meant that although STWs in cities would most likely have a bigger market availability, at least for vermicast, quality control would exert a significant influence on the actual access (in terms of product acceptability and not distance) to these markets.

In a study conducted by the Eastern Cape Development Corporation (ECDC, 1999) it was reported that there were only eight koi breeders in the whole of South Africa and that the main koi markets were located in Gauteng (70%) followed by Cape Town (15%) and Durban (10%). The market base in the Eastern Cape Province (2%) was not extensive and this meant that IWBFs would most likely have to transport their koi to markets in other Provinces. This has the potential to increase transport costs especially considering that koi are a perishable commodity. However, with the development of two of the country's purpose-built export zones namely the East London and Coega Industrial Development Zones, in the Eastern Cape Province, access to markets could increase together with increased transport routes and competition for trade which will most likely result in cheaper costs of transport.

Based on the above therefore it appeared that there was a local market for the vermicast and that markets for koi were located in other Provinces of South Africa. However, markets might be available to the first few established IWBFs but as more facilities are set up, the market would most likely become saturated because all facilities would be generating similar products. Therefore it might be necessary for some facilities to consider producing and selling worm-based fish feed instead of establishing an aquaculture process unit. In addition to avoiding saturated markets, another potential benefit is that the feed would be lighter and not perishable (if well processed) therefore transport costs would be reduced. Also, if pelleted, the feed could easily be sold on the export market and based on the current exchange rates with possible target countries (mainly in Asia); this alternative might be economically viable and potentially more profitable than producing koi. However, this is an area for further investigation.

4.3.4.2. Cost-benefit analysis

Table 4.6 provides a summary of the estimated capital, operational and maintenance costs and direct economic benefits of the IWBF. Details of the costs of each of the process units of the IWBF (HRAP, composting, vermicomposting and aquaculture) are provided in Appendix III of this thesis. Data regarding the initial capital costs for each of the IWBF's process units was readily available, although this was not the case for the costs of operation and maintenance. This lack of information was regarded as one of the most significant draw-backs of the TA process and will be discussed in more detail in Section 4.4.

All cost estimates were based on a 1ML/day IWBF and details of the quantity of inputs and products generated from this size facility were provided in section 4.3.1.2 and will not be repeated. It has been assumed that a conditioned and dewatered sludge cake with 40% dry solids would be the input product into the facility therefore pre-treatment costs have been excluded. Average construction costs were used in the calculations (Appendix III) but may have been over estimated in the case of those facilities where certain infrastructure was already in place. It is also important to note, that the findings of the cost-benefit analysis were based on the best case scenario i.e. that the system was 100% efficient and that inputs into the facility equalled the outputs.

It must also be noted that due to the potential variation in the market value of the various products, and limited resources, it was necessary to make use of estimated market values based on the mean of reported prices. The value of algal biomass was reported to range from R 54 750 to 82 125 annually for a facility producing 75kg/ha/day (Rose *et al*., 1996) i.e. 1kg=R 2.50 and, based on a series of values cited by Edwards (1998) and a plant nursery in Port Elizabeth that sells vermicast, the retail price of was approximately R 20 000 per ton. The retail value of vermicast was based on literature because none of the farmers or nurseries in the Eastern Cape Province was presently selling vermicast in their establishments. The value of worms on the market as obtained during a semi-structured interview with Grahamstown Pet Supplies (June, 2005) was estimated at R 20 per kg while the potential income from koi was based on figures obtained from four local pet shops (Cape Koi aquarium, Grahamstown pet shop, Rainbow aquarium and Finny Flipper- located in Cape Town, Grahamstown, Port Elizabeth and East London respectively) which showed that the average retail price of a single 10-12cm koi, irrespective of gender, was R 1795. It was assumed that koi would be harvested once a year (no re-stocking and no births) and worms would be available five times a year (every 66 days). The last batch of worms (sixth time) has been excluded from the calculations because these worms would need 33 more days to develop to maturity.

The calculations provided in Table 4.6 also include the costs of labour which were based on South Africa's average minimum wage payment for municipal workers-R 2200 per month for semi-skilled/unskilled workers, R 8000 for skilled workers, R 20 000 for highly skilled workers and R 32 000 for managers (Department of Labour, 2005). The costs of the two skilled managers that will be running the facility (one for the ponds-HRAP, aquaculture and one for composting and vermicomposting units) have been incorporated into the costs for the aquaculture and vermicomposting facilities. All costs and incomes have been rounded off to the nearest whole number. The costs of retailing compost were excluded from the calculations since all compost will be sent to the vermicomposting unit for conversion into a higher value product and therefore no residual compost will be available. The potential economic benefits that could be obtained from the sale of the bulking material used in the composting process unit as mulch have also been excluded from the table because all available bulking material will be re-used in the composting process unit reducing replacement costs.

Table 4.6: Estimated costs and benefits associated with the construction and operation of a 1ML/day IWBF

PROCESS UNIT	**COST**		**BENEFIT**	
	Initial capital costs	**Annual cost of maintenance and operation cost**	**Product**	**Annual potential income**
HRAP (2)	R 276 000	R 548 800	Algae	R 91 250
COMPOSTING	R 286 960	R 297 372	-	-
VERMICOMPOSTING	R 235 120	R 707 700	Vermicast	R 817 600
			Worms	R 27 700
AQUACULTURE	R 463 342	R 705 100	Koi	R 4 986 510
IWBF	**TOTAL CAPITAL COST R 1 261 422**	**TOTAL ANNUAL COST R 2 294 972**	**TOTAL ANNUAL INCOME R 5 923 060**	

Although Table 4.6 indicates that the potential income from a 1ML/day facility exceeds the start-up, operational and maintenance costs, to analyse the profitability of any technology, its net present value (NPV) must be determined (Martin pers. comm., 2005). The NPV determines the relative benefit of a technology over a certain period of time versus the initial start-up cost (t=0) and the operational costs over the same time period. In this way, it is also possible to determine the amount of time it will take to "break even". Once calculated, if the NPV is positive, then the project/technology may be worthwhile at least from an economic point of view. Likewise, if the NPV is negative, the project/technology may not be worthwhile from an economic point of view because cash-flows will also be negative.

Using a prime interest rate of 12% as obtained from the South African Reserve Bank (July, 2005), the initial investment costs of a 1ML/day IWBF (Table 4.6) and expected income (benefits) in the first year of operation, the NPV was calculated (Box 2) and found to be R 1 977 942. Therefore, from an economic point of view the NPV indicated that the proposed IWBF is theoretically economically viable.

BOX 2

NPV= -Initial capital costs + Present value of future net benefits

NPV =-1 261 422 + [3 628 088 / (1 + 0.12)]
NPV = 1 977 942

Where:

Future net benefit = 5 923 060 – 2 294 972
n= 1 (one year)

The benefit-cost ratio (BRC= total fixed costs/total net benefit) was also determined and found to be approximately 1:3 (initial capital costs: net income) which means that the project would not be able to cover approximately three times its potential costs within the first year of operation. However, during subsequent years, if any equipment needed to be replaced, then the BRC could be affected directly as a result of this 'additional fixed cost' (Martin pers. comm., 2005). It is important to note however that since some of the process unit operations, such as composting are well known to benefit from economies of scale (Marx *et al*., 2004), the economic viability could potentially increase with plant size. Additionally, the costs and income gained by STWs are likely to vary not only with the sizes of the STWs but with location. Unfortunately, due to a series of constraints primarily resource and confidential nature of financial information, the current study could not include a more detailed economic analysis for each of the nine sample STWs.

The costs of infrastructure of the IWBF were not considered a potential barrier at five of the nine sample STWs (Graaff Reinet, Belmont River Valley, Cradock, Driftsands and Cape Receife) because existing sludge drying beds could be used for composting and vermicomposting. For example at a STW such as Driftsands, a fully functional high-rate composting infrastructure already exists (although it has never been used). As such, the initial

capital outlay at this facility would potentially be lower than at the other sites where suitable infrastructure is not in place. However, additional infrastructure such as net shading to protect worms in the vermicomposting units from direct sunlight and predation by birds would be required at all nine sample STWs. With regards to the ponds (HRAP and aquaculture) infrastructure will have to be built at all sample STWs except Belmont River Valley STW which already has in existence an Integrated High Rate Algal Pond (IHRAP) system run by the Rhodes University Environmental Biotechnology Group. However, the current IHRAP system at this STW is suited to polish 0.75ML/day therefore additional HRAPs and ASTs would still need to be constructed to match existing daily flow rates (5.14ML/day).

The above findings include a potential reduction in running costs of municipal STWs. The proposed IWBF possesses the ability to reduce the overall need for chemicals and related costs at all nine sample STWs. Dekker (2002) suggested that "*effluent from the HRAP is highly alkaline and may be recycled upstream for the control and neutralisation of influent acidity…..This would eliminate or reduce the need for lime to increase pH*". However, the feasibility of this has yet to be tested and investigation is required in further studies. Aquaculture is the only process unit of the IWBF that requires chemicals where as previously indicated (Chapter 3, section 3.3.3.1) zeolite and 2 phenoxy-ethanol would be needed during transportation of koi to the market. In the long-term, the pressure on municipal budgets by STWs are likely to be reduced allowing larger budgets for other millennium development goal initiatives such as education, housing, other sanitation and health projects. The IWBF minimises the need, and therefore costs, for chemical disinfectants to be used in wastewater treatment due to improved pathogen removal from 'treated' effluent by the HRAP.

It is also important to note that the potential economic benefits from the proposed IWBF would have consequences for the current users of the sludge generated at STWs such as Fish Water Flats STW because if the proposed IWBF were established at this STWs, Coega Brick, the current users of sludge from the Fish Water Flats STW would potentially have to buy more coal for the brick-making process. However, the current TA determined that the proposed IWBF was not suitable for this particular STWs due to the lack of sufficient land for its establishment (4.3.3.1).

4.3.4.3. Affordability

Affordability does not only refer to the financial ability to procure the system but also the STW's access to resources for maintaining the technology at top performance throughout its useful service life. The latter does not present a problem because with good financial management, the system should be self-sustaining after a very short period (see Section 4.3.4.2 above). Therefore, although it has been demonstrated that the proposed IWBF is, under ideal conditions, financially viable, it was necessary to ascertain whether municipalities and STWs had access to the necessary start-up capital. These start-up costs of the IWBF have to be considered in terms of municipal budgets for sanitation. Unfortunately it was impossible for the current study to gain access to the budgets for any of the nine sample STWs or the relevant local municipalities as these were confidential.

While relatively cheap compared with other technologies, the funds involved in the establishment of the IWBF are likely to be significant to smaller municipalities. However, although larger facilities such as Fish Water Flats and Kelvin Jones potentially have bigger budgets because they serve larger populations, it is highly unlikely that any of the nine sample facilities would be able to afford the capital costs of the proposed IWBF as reflected in the findings of studies conducted by Antrobus (2003) and Mohale (2003) who found that no upgrading of existing infrastructure had occurred at overloaded STWs, a situation which could largely be attributed to their lack of funds. The lack of financial resources for construction of the IWBF is potentially a significant barrier to its establishment. This being the case, it is suggested that STWs would either have to investigate the possibility of public-private partnerships or approach foreign donors such as the German Technical Corporation (GTZ) or the Swedish International Development Agency (SIDA), both well known for funding sanitation-related projects in Southern Africa.

Public-private partnerships are ideal because the IWBF appears to be a good investment and can additionally be taken on as part of social responsibility initiatives. However, if these two approaches fail to provide municipalities with the necessary start-up capital, they will most likely have to borrow the initial capital costs directly from lending institutions such as the World Bank Group and the African Development Bank (AfDB) Group. These institutions tend to finance specific projects and although the World Bank (2003) reported that aid flows

to Africa declined by 40% per capita in the past decade, this situation has changed. Between the years 2000-2003, there were increased lending commitments by the World Bank's International Development Corporation (IDC) towards the water and sanitation sector in Sub-Saharan countries from US $112.2 million to US $296.3 million (World Bank, 2003). However, despite this, securing loans for projects such as the proposed IWBF from branches of the World Bank would probably not be easy for countries such as South Africa because the World Bank's IDC has only 37 countries it considers 'eligible borrowers' in Sub-Saharan Africa and South Africa is not one of them (World Bank, 2003). Therefore STWs in South Africa might have to rely on foreign donor agencies.

The ability of STWs to afford the proposed IWBF will also be dependant on factors such as location particularly since it has the ability to influence the costs and benefits of the proposed technology. This issue is discussed extensively below.

4.3.4.4. Location

The net income from an IWBF is likely to vary with location due to a variety of factors including the distance from suppliers of construction materials, technical and construction experts and markets for products. The latter, together with the quantity of products, will have a direct influence on transportation costs. The mode of transport would also influence costs for example; if local markets for products were adequate then it is probable that the STWs would rely on road transport. However, if distant markets were targeted, more costly air transport could be required. The latter is particularly true for koi which, as previously indicated (Section 4.3.4.1), would be sold primarily in other Provinces of South Africa (Gauteng, Western Cape, Kwazulu-Natal). Thus, the transport costs of this perishable commodity would most likely be high for IWBFs established at more remote STWs (Cradock, Graaff Reinet, Belmont River Valley, Kwanobuhle, Kelvin Jones and Despatch).

Table 4.7 summarises the effect location could have on the economic viability of the IWBF at each of the nine sample STWs. In the table, with regards to the distance from materials and markets, "close" was considered <50km, "intermediate" was 50-150km and "far" was >150km. The effects of location on the costs of labour have been excluded from the table because labour costs were thought to be similar irrespective of location (Section 4.3.4.2).

Table 4.7: The effect of location on factors that will affect the economic viability of the IWBF at nine sample STWs in the Eastern Cape

Name of STW	**Distance from materials**	**Availability of labour**	**Distance from markets**	**Transport costs of products to markets**
Fish Water Flats	Close	High	Close	Low
Driftsands	Close	High	Close	Low
Cape Receife	Close	High	Close	Low
Kelvin Jones	Intermediate	Medium	Intermediate	Medium
Kwanobuhle	Intermediate	Medium	Intermediate	Medium
Despatch	Far	Medium	Far	High
Belmont River Valley	Far	Medium	Far	High
Graaff Reinet	Far	Medium	Far	High
Cradock	Far	Medium	Far	High

Table 4.7 indicates that there will most likely be differences in the availability of sufficiently skilled labour depending on location which might in turn influence the costs. However, as previously discussed in Section 4.3.1.4., the availability of highly skilled experts required to solve complex biological problems will not present a problem at any of the nine sample STWs. Of the nine sample STWs, Fish Water Flats, Kelvin Jones, Kwanobuhle, Driftsands and Cape Receife are not likely to experience problems related to the availability of labour particularly semi-skilled/unskilled due to their close proximity (less than 50km) to the city of Port Elizabeth. In addition, in the majority of developing countries the trend is for people (mostly unskilled labour) to 'flock' to large cities in search of employment opportunities (Waugh, 1999).

Table 4.7 also indicates that the distance from materials and markets will be low (nearer) for STWs located in large cities (Port Elizabeth, Driftsands, Cape Receife) when compared to that for STWs in small towns. These two aspects have already been discussed in Sections 4.3.1.4

and 4.3.4.1 and will not be repeated. However, these aspects together with the quantity and nature of products will strongly influence transport costs. With regards to the latter, it is suggested that although STWs located in large cities may have lower transport costs particularly of products to the market, due to their close proximity, these costs could be increased by the quantity of goods they will be transporting. It was determined in Chapter 2 (Section 2.3.2) that STWs located in large cities are producing the largest volumes of wastewater and sludge and, therefore, would produce more product from the IWBF.

The assessment of the economic sustainability of the IWBF indicated that although the system was under ideal conditions economically viable, the net income would be influenced by location. This was due to the influence of location on vital aspects such as availability of markets, transport costs, value of products, costs of construction, operation and maintenance, and labour and skill availability. This emphasised the need for detailed site-specific investigations into these aspects prior to the procurement of any technological system, including the IWBF. Importantly the assessment also indicated that while markets existed for the vermicast, potential buyers/users were concerned about potential health risks and therefore the access to these markets would be determined by product quality.

4.4. GENERAL DISCUSSION

Through the use of a modified TA methodology, incorporating four sustainability indicator categories, it was demonstrated that for all sustainability indicator categories (technical, social, environmental, economic) under ideal conditions the proposed IWBF has the potential to be sustainable. However, good planning, proper management and maintenance were regarded as vital to the success of the system.

The potential positive impacts of the system included the reduction of health and nuisances, creation of direct and indirect employment and the generation income through the sale of a range of products. Potentially significant negative impacts of the system included the production of leachate and subsequent contamination of water resources, the formation of odours and increased pressure on already strained municipal budgets due to the economic demands of the system. However, production of leachate and odour formation could be overcome if preventative measures are taken during the design, construction and operation of

the system. The controversy still surrounding the use of sludge-based fertiliser, the need for some STWs to remove people from land, the lack of vacant land and the lack of financial resources for construction were considered the primary barriers to implementation. The lack of sufficient land was particularly significant at the two largest STWs, namely Fish Water Flats and Kelvin Jones and it was therefore unlikely that the IWBF would be suitable for larger facilities. One of the most significant factors highlighted by the TA was the importance of location in determining the likely sustainability of the IWBF since it could affect the economic viability of the system, the magnitude of environmental impacts and the ability of the technology to meet the outcomes for which it was designed.

While the assessment of the technical, social, environmental and economic sustainability was considered sufficiently detailed to identify any significant barriers to implementation of the proposed IWBF at nine sample sites in the Eastern Cape and aspects to be considered during the design and operational stages, certain elements were considered to require site-specific pilot studies prior to proceeding with full-scale implementation of the technology. These included:

- The decline in production in the composting, vermicomposting and HRAP units of the IWBF during winter months;
- The effect of seasonal changes on the quality of products;
- The bioremediation properties, specifically heavy metal uptake by worms in the vermicomposting process unit of the IWBF;
- The health risks associated with the handling and use of sludge-based vermicast;
- The potential occupational hazards to workers at composting sites as a result of bioaerosols;
- The exact long-term value and size of the market for vermicast; and
- The value of worm-based fish meal relative to the value of koi and fresh worms.

While the current version of the TA was regarded as useful for the identification of barriers to implementation of the IWBF and, indeed, other technologies in developing countries, during execution of the TA, certain constraints including a lack of information, the challenge of

interpreting available information and resource constraints were experienced. Each of these is discussed below.

During the TA it was found that in some cases information did not exist or was proprietary. In the case of the former, trying to obtain the information proved to be a challenge because the process was resource intensive (time and money) and data was often incomplete. As the system being assessed was conceptual, the TA relied heavily on indirect sources of information. It was also ascertained that as determined by Callens & Tyteca (1999), "*it is usually not a lack of measures that hinders the evaluation of technologies, but the overwhelming abundance of potentially useful measures and indicators*". During the current TA determining which information was vital and which was not (i.e. what indicators to use) proved a difficult task. As a result, some factors/criteria that could have otherwise been considered indispensable by some scholars may not have been considered in this TA. Therefore, in agreement with Ludwig (1997) and Van Eijndhoven (1997), the major "*TA dilemma*" is not the development of suitable TA methodologies, but the development of suitable sustainability criteria that can be used to guide these methodologies and the assessment process. The controversy and debate surrounding the selection of suitable sustainability criteria emphasises the need for TAs to be conducted by a multi-disciplinary team of independent researchers as this factor is likely to reduce the element of subjectivity. Interested and Affected Parties (I&APs) should be consulted prior to the initial assessment and all should agree on the criteria for the assessment of sustainability within the local context. I&APs should also be involved after the initial assessment to determine whether or not there is agreement as to the outcome of the process.

Development of sustainability criteria needs to be explored and investigated further. The set of sustainability criteria used in the current TA were believed to be an improvement on existing ones because they attempted to exhibit a sufficient understanding of the limitations and needs/priority issues in developing countries. Additionally, while it would be useful to have a central list of suitable sustainability indicator categories, this 'Master List' must be adapted to take local needs, priorities and resource availability into account. In addition, while the TA methodology employed in the current study was considered inclusive of all key aspects of sustainability, the relative importance of the various sustainability criteria was

considered context-specific. Elkington (1997) acknowledged the difficulty and sometimes impossibility of technologies being selected against "a triple bottom line" due to the reality that the overall sustainability of technologies particularly in developing countries is usually overlooked because irrespective of environmental and social benefits, economic sustainability is often ultimately the deciding factor as to the 'sustainability' of a technology. The current TA indicated that the proposed IWBF was not economically viable and there were other potential barriers to implementation that required consideration e.g. public acceptability, land availability etc. Thus, a paradigm shift is required to address this, however, with the current debate surrounding the notion of 'sustainability' the selection and development of suitable 'sustainability' criteria might prove to be a more challenging task.

4.5. CONCLUSIONS

Based on the TA with the various limitations discussed above, the benefits of the proposed IWBF would, at the majority of sample sites, outweigh the potential negative impacts and thus investigations should continue on pilot-scale facilities. Notwithstanding the above, the IWBF was considered inappropriate at a number of sites due to space constraints. Furthermore, certain potential barriers required further investigation to determine their significance with greater certainty. The most important factor that was highlighted by the TA was the importance of location in determining the overall sustainability (environmental, economic, social, technical) of a technology. The need to re-think current TA methodologies and to address associated constraints allowing the tool to be used and fully comprehensive was also highlighted.

CHAPTER 5

GENERAL DISCUSSION AND CONCLUSIONS

Some of the consequences of halving the proportion of people without access to basic sanitation by the year 2015 may not have been adequately foreseen during the planning and development of the Millennium Development Goals (MDGs). For a country such as South Africa, this MDG has directly resulted in a significant increase in the provision of waterborne sanitation (Marx *et al*., 2004) which may be viewed as problematic for a number of reasons. The proportion of households having access to sanitation increased from 49% of households in 1994 to 63% in 2003 (DNH & PD, 2005). As a direct result, there appears to have been volumetric and organic overloading of existing STWs (Antrobus, 2003; Mohale, 2003), increased water consumption in a region considered "water stressed" (DEAT, 2000) and increased sewage sludge requiring safe disposal. The current research revealed that the latter currently posed a potential threat to the environment (particularly water resources) and, to a somewhat lesser extent, human health. Furthermore, it is proposed that increased sewage sludge production, a lack of capital to acquire and operate applicable treatment technologies and a lack of incentives for improved management is likely to result in sludge being disposed of in an uncontrollable manner as was found at certain STWs in the Eastern Cape Province of South Africa (Chapter 2).

The above dilemma entrenches the need for South Africa and other developing countries to establish appropriate measures to manage sewage and sewage sludge. Societies' attitudes and management practices regarding wastes including sewage sludge and wastewaters need to be changed. Management of wastes should adhere to the principles of the waste management hierarchy as set out in the National Waste Management Strategy (DEAT, 2000) and the White Paper on Integrated Pollution and Waste Management (DEAT, 2000). Disposal should be regarded as the last option, and if necessary, must be done in a manner that minimizes negative impacts on environmental and human health. Wherever possible, reuse and recycling should be investigated and may lead to the establishment of economic incentives that could lead to improved management and reduce the financial burden often associated with waste management. Sound economic-based incentives may well negate the need for the "command and control" approach to waste management which was seen as largely ineffectual with

regards to the management of sewage sludge. It was clear that legislation alone has been unable to address the problem primarily due to the inability of authorities to enforce it. Despite this, a cost-effective and innovative solution to improving the sewage and sludge management problem while responding to regulatory and public pressures still needed to be found particularly for metropolitan cities.

Adopting an industrial ecology approach to the way in which modern communities are designed allows waste management not to be viewed as the end of the line, but rather as a key component of the materials cycle of a community. The industrial ecology approach allows for the provision of economic incentives (turning waste into wealth) while minimizing potential negative environmental impacts. As with many of the other stages in the community cycle, it would have inputs and result in the production of products and limited wastes. Sale of the products would off-set capital and operational costs of production and treatment. Adoption of this philosophy is essential if modern society is to be ecologically sustainable.

Highly integrated systems for waste management and beneficiation have existed for centuries (White *et al*., 1995; White, 1997; McDougall, 2000) and many of the fundamental concepts have been applied to modern environmental problems through the concept of ecologically engineered systems (Todd *et al*., 2003). However, while highly applicable in modern society, there were no guidelines as to the rational design of such systems so that they are able to address all the problems of a particular context. The Integrated Waste Beneficiation Facility (IWBF) also highlighted the value of integrated systems in modern society. It allowed sludge to "pay for itself" (additional beneficiation opportunities) in so doing indicating to governments and external lending agencies that despite the inherent nature of waste management, it is still a sector that can easily generate revenues therefore reducing the risk of providing loans to waste management initiatives. In addition, even if the treatment of municipal effluent is of sufficient standard, the inclusion of an HRAP will provide a "free" buffer to protect natural water resources during periods when the conventional system fails.

Although Chapter 2 of the current study ascertained that such a system was required, particularly in metropolitan cities, the largest sludge producers, Chapter 4 indicated that the proposed IWBF might not be ideal for larger STWs most of which tend to be located in

metropolitan cities. This highlighted two issues. The first one was the need for proper long-term planning and management not only in the water and sanitation sector but in land use planning as well. The latter is because as indicated, although a potential solution to the sludge management problem was proposed, the two largest STWs assessed in the current study were not suitable candidates for implementing the proposed IWBF due to the lack of available land for construction of this system. The second issue highlighted was the importance of technology assessments (TA) which will assist in the long-term planning process by revealing the various direct and indirect impacts of proposed technologies. It is important that TAs incorporate more than simply economic considerations. This was highlighted in the current study because if only the economic sustainability of the IWBF had been considered then it would have been applicable at all sample STWs. However, inclusion of resource analysis revealed that land availability excluded the technology from certain areas. Additionally, information obtained from TAs could then be used to decide whether a technology met the immediate and/or long-term goals of a society. The immediate provision of water-borne sanitation to meet the MDGs is an example where short-term needs are being addressed without the consideration of the long-term suitability and sustainability.

The current study therefore highlighted the need for the provision of sanitation to be tempered until a full context-specific Technology Assessment (TA) has been concluded. This is important because it allows governments and proponents of technologies to determine the consequences of technologies before implementation. Additionally, alternative sanitation technologies including dry-urine diversion systems should be considered and compared with existing methods by means of the modified TA methodology. The outcomes of such a TA exercise could then be used to inform development policy (including sanitation provision) at national, provincial and local government levels.

In summary, this research served to highlight:

- The potential environmental and health threats associated with current sewage sludge management in the Eastern Cape Province of South Africa thereby emphasizing the need for improved management;

- A rational design approach (Chapter 3-Figure 3.1) to novel ecologically engineered systems suited to a particular developing country's needs primarily in the wastewater and sanitation sectors;
- The design and assessment of an IWBF able to address current shortfalls in sewage treatment and sludge management, while providing potential additional non-regulatory incentives;
- The need to re-think current TA methodologies and to address associated constraints in order to allow the tool to be used and fully comprehensive resulting in the selection of appropriate technologies for future use in developing countries.

While an initial assessment of the IWBF technology indicated that it would be able to address existing sanitation problems in an economical and sustainable manner, certain further research was required. Suggestions for future research include:

- National surveys not only in South Africa but in other developing countries of wastewater treatment plants, their treatment processes, sludge quantities and qualities as well as current sludge utilization/disposal routes and related environmental, economic and social implications;
- The bioremediation properties of worms and quantification of their degree of heavy metal uptake especially during the vermicomposting process;
- Further detailed risk assessment of the health risks associated with current sewage sludge disposal practices so as to reduce the risks for surrounding communities and those working on site at STWs;
- Establishment and detailed assessment (economic, technical, environmental and social) of pilot-scale IWBFs at different locations, including the market potential of the various products;
- The application of the proposed TA and rational design methodologies in other contexts but specifically in developing countries.

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APPENDICES

Appendix I: The sewage treatment technologies currently employed at each of the sewage treatment facilities in the Eastern Cape Province of South Africa that are producing and treating sludge.

East London area

	NAME OF STW	SEWAGE TREATMENT TECHNOLOGY	AMOUNT OF WASTEWATER TREATED (ML/DAY)	MASS OF SLUDGE GENERATED (PRIMARY + WASTE ACTIVATED) tDS/day
1	Burgersdorp	Activated plant	2.9	1.015
2	Butterworth	Activated plant	3	1.05
3	Cathcart STWs	Activated plant	1.5	0.525
4	Central	Bio-filtration	5	1.75
5	DaGama	Activated sludge	0.1	0.035
6	DaGama: Zwelitsha	Activated plant	3.5	1.23
7	Dimbaza	Activated sludge	6	2.1
8	East Bank Reclamation Works	Activated plant	40	14
9	Fish River Sun	Activated plant	1	0.35
10	Fort Hare: Alice	Activated sludge	2	0.7
11	Johnson&Johnson	Activated sludge plant	1	0.35
12	Keiskammahoek	Activated sludge plant	1	0.35
13	King Williams Town	Activated sludge Biofiltration	5	1.75
14	Mdantsane	Biofiltration	10	3.5
15	Middledrift	Activated sludge	0.25	0.087
16	Mpekweni Sun	Biodisc unit	0.5	0.175
17	Nahoon	Activated sludge plant (small unit)	0.5	0.175
18	Peddie	Activated sludge	0.3	0.105
19	Potsdam	Bio-filters	9.2	3.22
20	Queenstown	Activated sludge and biofiltration	12	4.2
21	Seymour STWs	Activated sludge plant	0.25	0.087
22	Sterkstroom	Activated sludge plant	0.94	0.329
23	Stutterheim	Activated sludge	1.5	0.525
24	Whittlesea	Biofiltration	1.2	0.42
25	Zwelitsha	Biofiltration	18	3.06

Port Elizabeth area

	NAME OF STW	SEWAGE TREATMENT TECHNOLOGY	AMOUNT OF WASTEWATER TREATED (ML/DAY)	MASS OF SLUDGE GENERATED (PRIMARY + WASTE ACTIVATED) tDS/day
26	Adelaide	Activated sludge plant	1	0.35
27	Boesmans River	1 biofilter	1	0.35
28	Boskor Boskor	Biofilter-Pretech West and East plants	1	0.35
29	Cape Receife	Activated sludge	12	4.2
30	Coldstream	Biofilter system	4	1.4
31	Cradock	Activated sludge plant, rotating disc biofilter plant combined with reactivated sludge plant.	4.8	1.692
32	Despatch	Activated sludge plant, rotating disc biofilter plant combined with reactivated sludge plant.	4.6	1.61
33	Driftsands	Activated sludge	5-10	2.63
34	Fish Water Flats	Activated sludge, biofilters	112	39.2
35	Fort Beaufort	Activated sludge	2	0.7
36	Graaff Reinet	Activated sludge plant combined with biofilter plant	3	1.05
37	BelmontValley	Biological filtration	5.14	1.799
38	Grootfontein Agric. College	1 biofilter	0.089	0.03
39	Humansdorp	Activated sludge, Seskoi River (biofiltration)	4	1.4
40	Joubertina	Activated sludge, Kroom River (biofiltration)	1	0.35
41	Kelvin Jones	Activated sludge	22	7.7
42	Kirkwood	New activated sludge	0.336	0.117
43	Kirkwood correctional	Biofilter sludge plant	0.77	0.269
44	Kwanobuhle	Reactivated sludge plant	7.8	2.73
45	Lottering State Forest	Biofiltration plant	1	0.35
46	Middleburg	2 biofilters	1	0.35
47	St. Albans Prison	Activated sludge	1	0.35
48	St. Francis Bay	Activated sludge	1	0.35
49	Witelsbos	Biofilters (Die Blaar and Kwaaaibrand)	1	0.35

Umtata area

	NAME OF STW	SEWAGE TREATMENT TECHNOLOGY	AMOUNT OF WASTEWATER TREATED (ML/DAY)	MASS OF SLUDGE GENERATED (PRIMARY + WASTE ACTIVATED) tDS/day
50	Mazamba village market	Biodisc	0.03	0.10105
51	Umtata	Biological filtration	12	4.2
52	Wild Coast Sun	Activated sludge	1	0.35

Appendix II: Detailed environmental, social and economic risk assessment results

SOCIAL FACTOR	FACILITY	PROB.	TEMPORAL	SPATIAL	CERTAINTY	SEVERITY	RISK
Location/distance of the sludge disposal site in relation to the nearest human settlement, and as a result posing a nuisance	Fish Water flats	1	3	1	2	1	8
	Driftsands	2	3	1	3	2	11
	Cape Receife	2	3	1	3	2	11
	Kwanobuhle	3	3	2	4	3	15
	Kelvin Jones	2	3	1	3	1	10
	Despatch	2	3	1	3	1	10
	Belmont valley	2	3	1	4	3	13
	Cradock	3	3	2	4	3	15
	Graaff Reinet	3	3	1	4	3	14
Use of polluted water body by surrounding communities	Fish water flats	1	1	1	1	2	6
	Driftsands	2	2	5	1	2	12
	Cape receife	2	2	5	1	2	12
	Kwanobuhle	3	3	1	4	3	14
	Kelvin Jones	1	1	1	1	2	6
	Despatch	2	2	1	1	2	8
	Belmont valley	2	3	3	1	3	12
	Cradock	2	2	1	1	2	8
	Graaff Reinet	1	1	1	1	2	6
Potential risk of bacterial, viral and parasitic diseases transmitted through the food chain	Fish water flats	1	1	1	1	2	6
	Driftsands	2	2	1	4	3	12
	Cape receife	3	3	1	4	3	14
	Kwanobuhle	2	3	1	3	3	12
	Kelvin Jones	1	1	1	1	2	6
	Despatch	2	2	1	3	2	10
	Belmont valley	2	3	1	4	3	13
	Cradock	3	3	1	4	3	14
	Graaff Reinet	1	2	1	2	2	8

SOCIAL FACTOR	FACILITY	PROB.	TEMPORAL	SPATIAL	CERTAINTY	SEVERITY	RISK
Presence of vectors/insects which pose a nuisance and may cause disease	Fish water flats	2	3	1	1	2	9
	Driftsands	1	3	1	4	2	11
	Cape receife	1	3	1	3	2	10
	Kwanobuhle	3	3	2	4	3	15
	Kelvin Jones	2	3	1	1	2	9
	Despatch	1	3	1	3	2	10
	Belmont valley	1	3	1	3	2	10
	Cradock	3	3	2	4	3	15
	Graaff Reinet	3	3	2	4	3	15
Potential odour problems which may pose a nuisance	Fish Water flats	3	3	2	4	3	15
	Driftsands	3	3	1	4	3	14
	Cape Receife	3	3	1	4	3	14
	Kwanobuhle	3	3	2	4	3	15
	Kelvin Jones	3	3	1	4	3	14
	Despatch	3	3	1	4	3	14
	Belmont valley	3	3	1	4	3	14
	Cradock	3	3	2	4	3	15
	Graaff Reinet	3	3	2	4	3	15
Potential risk of dust/disease being spread by wind	Fish Water flats	2	3	2	2	3	12
	Driftsands	1	1	1	1	2	6
	Cape Receife	1	1	1	1	1	5
	Kwanobuhle	2	3	2	3	3	13
	Kelvin Jones	1	2	1	1	2	7
	Despatch	1	1	1	1	2	6
	Belmont valley	1	3	1	1	3	9
	Cradock	2	3	2	3	3	13
	Graaff Reinet	2	3	2	2	2	13

ECONOMIC FACTOR	FACILITY	PROB.	TEMPORAL	SPATIAL	CERTAINTY	SEVERITY	RISK
Potential wastage of sludge as a resource of economic value	Fish water flats	0	0	0	0	0	0
	Driftsands	3	3	6	4	2	15
	Cape receife	3	3	6	4	2	15
	Kwanobuhle	3	3	6	4	2	15
	Kelvin Jones	3	3	6	4	2	15
	Despatch	3	3	6	4	2	15
	Belmont valley	3	3	6	4	2	15
	Cradock	3	3	6	4	2	15
	Graaff Reinet	3	3	6	4	2	15
Methane produced is not collected and either flared or used as an energy source	Fish water flats	0	0	0	0	0	0
	Driftsands	3	3	3	4	3	16
	Cape receife	3	3	3	4	3	16
	Kwanobuhle	3	3	3	4	3	16
	Kelvin Jones	3	3	3	4	3	16
	Despatch	3	3	3	4	3	16
	Belmont valley	3	3	3	4	3	16
	Cradock	3	3	3	4	3	16
	Graaf Reinet	3	3	3	4	3	16
Sludge disposal methods affect surrounding land use	Fish water flats	1	3	1	3	1	9
	Driftsands	3	3	2	1	1	9
	Cape receife	3	3	2	3	3	14
	Kwanobuhle	3	3	3	4	3	16
	Kelvin Jones	2	2	1	2	3	9
	Despatch	2	2	1	2	3	9
	Belmont valley	3	3	1	4	3	14
	Cradock	3	3	3	4	3	16
	Graaff Reinet	3	3	3	4	3	16

ENVIRONMENTAL FACTOR	FACILITY	PROB.	TEMPORAL	SPATIAL	CERTAINTY	SEVERITY	RISK
Transportation of contaminated soil/sludge into nearby water courses resulting in water pollution	Fish Water flats	1	3	1	2	2	9
	Driftsands	3	3	5	2	3	16
	Cape Receife	3	3	5	2	3	16
	Kwanobuhle	3	3	2	3	3	14
	Kelvin Jones	2	3	3	3	3	14
	Despatch	2	2	1	2	2	9
	Belmont valley	3	3	3	4	3	16
	Cradock	2	2	1	3	2	11
	Graaff Reinet	2	2	1	3	2	11
Potential risk of air pollution	Fish water flats	1	1	2	1	2	7
	Driftsands	3	3	1	3	3	13
	Cape receife	3	3	1	3	3	13
	Kwanobuhle	3	3	3	4	4	17
	Kelvin Jones	3	3	1	3	3	13
	Despatch	3	3	3	4	4	17
	Belmont valley	3	3	1	4	3	14
	Cradock	3	3	3	3	4	16
	Graaff Reinet	3	3	1	3	3	13
Presence of avian creatures, that could get or transport diseases/get killed	Fish water flats	2	3	1	3	2	11
	Driftsands	2	3	1	1	2	9
	Cape receife	1	2	1	3	2	9
	Kwanobuhle	3	2	1	4	2	12
	Kelvin Jones	3	3	1	4	2	13
	Despatch	2	3	1	1	2	9
	Belmont valley	2	1	3	3	2	11
	Cradock	2	3	1	1	2	9
	Graaff Reinet	3	3	1	4	2	13

Appendix III: Annual capital, operational and maintenance costs of each of the process units of the IWBF.

Costs of a single High Rate Algal Ponding System (HRAP) polishing 1ML/day.

(Source: Rose *et al*., 1996; Department of Labour, 2005)

	Quantity/Unit	**Cost (Rand)**
Capital cost		
Cost of paddle wheel	1	22 000
Cost of motor	1	12 000
Earthworks construction and water seal liner		
Channel dividers		100 000
Total capital cost		4000
		138 000
Cost of operation and maintenance		
Personnel cost (1 semi-skilled/unskilled permanent, 1 temporary highly skilled)	2	266, 400
Electricity cost		3000
Civil works		1500
Mechanical and electrical equipment		3500
Total annual cost of operation and maintenance		**274 400**

Costs of a typical composting facility processing 0.35tDS/day

(Sources: Department of Labour, 2005; Dominguez *et al*., 1997; Horan pers. comm., 2005)

	Quantity/Unit	Cost (Rand)
Capital cost		
Construction costs		100 000
Chipper	1	89 000
Tractor	1	67 653
Trailer	1	10 000
Front end loader	1	20 307
Blower	1	100 000
Total capital cost		**286 960**
Cost of operation and maintenance		
Personnel cost (1 temporary highly skilled, 2 permanent semi-skilled/unskilled)	3	292 800
Electricity cost		1500
Cost of bulking agent		72
Civil works	0.12t	1000
Mechanical and electrical equipment		2000
Total annual cost of operation		**297 372**

Costs of a vermicomposting facility processing 0.35tDS/day

(Sources: Department of Labour, 2005; Dominguez *et al*., 1997; Edwards, 1998; Horan pers. comm., 2005; Port Elizabeth Nursery, 2005; Sherman, 2002)

	Quantity/Unit	Cost (Rand)
Capital cost		
Construction costs		100 000
Tractor	1	67653
Trailer	1	10 000
Front end loader	1	20307
Worms	1.75 tons	35000
Automatic Sprinkler	3	2160
Total capital cost		**235 120**
Cost of operation and maintenance		
Personnel cost (1temporary highly skilled, 3 permanent semi-skilled/unskilled)	4	319 200
Manager (for composting and vermicomposting process units)	1	384 000
Electricity cost		2000
Civil works		1000
Mechanical and electrical equipment		1500
Total annual cost of operation and maintenance		**707 700**

Costs of a typical 1111.2m^2 flow-through production aquaculture pond growing 2778 koi

(Sources: Cape Koi Aquarium-Cape Town, 2005; Department of Labour, 2005; Finny Flipper-East London, 2005; Grahamstown Pet Shop-Grahamstown, 2005; Jones pers. comm., 2005; Rainbow Aquarium-Port Elizabeth, 2005)

	Quantity/Unit	Cost (Rand)
Capital cost		
Pond construction (water seal liner and bird netting and wall to keep predators away)		120 000
Hand nets	5	30
Anchovy mesh seine nets with weights and floats (30x2m)	6	283
Fingerlings	2778	277 800
Filtration system		694
Heating system	4	36 500
Regulator	1	125
Aquarium air hose	50m	103
Buckets (6x20 litres)	2	80
Plastic drum (with lid to hold/transport fish)	210 litres	240
Air stones	12	84
12-volt air blower (to aerate transportation tanks)		8000
Portapools to hold fish before transportation	2	100
High volume low pressure blower (to aerate ponds)		15 000
2-phenoxy ethanol and zeolite		222
Coarse animal grade salt	25kg	88
Industrial oxygen cylinder	180 kgs	3993
Total capital cost		**463 342**
Cost of operation and maintenance		
Personnel cost (1 temporary highly skilled, 4 permanent semi-skilled/unskilled)	5	345 600
Manager (for HRAP and aquaculture)	1	348 000
Electricity cost		4000
Civil works		2500
Mechanical and electrical equipment		5000
Total annual cost of operation and maintenance		**705 100**

APPENDIX IV: Copy of the questionnaire used to survey the market potential of vermicast in the Eastern Cape Province

The questionnaire for nurseries:

1) In which town in the Eastern Cape Province is your nursery located/nearest to?

Please tick correct box below

Cradock	
Graaff Reinet	
Grahamstown	
Despatch	
Port Elizabeth	
Uitennhage	
Other (Please specify)	

2) How many customers does you nursery receive on average daily? (***This information will be kept confidential***)

Please tick correct box below

< 5	
5-10	
11-20	
21-30	
31-40	
41-50	
> 50	

3) Are you a specialist or general nursery?

SPECIALIST	
GENERAL	

4) Are you currently using vermicast in your nursery?

YES	
NO	

5-a) **If your answer to question 4 was yes**, please specify which vermicast products you are currently using.

Cattle manure	
Sewage sludge	
Vegetable matter	
Others (Please specify)	

Go directly to question 7 if you answered question 5-a

5-b) **If your answer to question 4 was no,** would you be willing to try using vermicast products?

YES	
NO	

Go directly to question13 if your answer to question 5-b was no

6) **If your answer to question 5-b was yes**, which of the following vermicast products would you be willing to try using?

Cattle manure	
Sewage sludge	
Vegetable matter	
Others (Please specify)	

7) How much are you currently spending or would you be willing to spend on buying vermicast for use in your nursery?

N.B: **Cost below is for five kilograms of vermicast.**

R20-50	
R50-100	
R100-150	
R150-200	

9) Do you sell vermicast products at your nursery?

YES	
NO	

10-a) **If your answer to question 9 above was yes**, which of the following vermicast products are you selling?

Cattle manure	
Sewage sludge	
Vegetable matter	
Other (Please specify)	

10-b) **If your answer to question 9 was no,** would you be willing to sell vermicast products at your nursery?

YES	
NO	

Go directly to question 13 if you answer to question 10-b was no

11) **If your answer to question 10-b above was yes**, which of the following vermicast products would you be willing sell?

Cattle manure	
Sewage sludge	
Vegetable matter	
Others (Please specify)	

12) How much money are you currently selling or would you be willing to sell vermicast in your nursery for?

N.B: **Cost below is for five kilograms of vermicast.**

R20-50	
R50-100	
R100-150	
R150-200	

13) Is there anything that concerns you about using/selling vermicast at your nursery?

YES	
NO	

15) **If yes**, please provide details

……
……

16) Do you think that other plant nursery owners would be **willing to use** vermicast on their establishments?

YES	
NO	

17) Do you think that other plant nursery owners would be **willing to sell** vermicast on their establishments?

YES	
NO	

Thank you very much for your cooperation.

The questionnaire for farmers:

1) In which town in the Eastern Cape Province is your farm located/nearest to?

Please tick correct box below

Cradock	
Graaff Reinet	
Grahamstown	
Despatch	
Port Elizabeth	
Uitennhage	
Other (Please specify)	

2) What is the size of your farm?

Please tick correct box below

$<5000m^2$	
$5000\text{-}10000m^2$	
$10000\text{-}20000m^2$	
$>20000m^2$	

3) Do you grow crops for commercial or subsistence purposes or both?

Commercial only	
Subsistence only	
Both of the above	
Other (Please specify)	

4) What are the main crops grown on your farm?

……

5) Are you currently using vermicast on your farm?

YES	
NO	

6-a) **If your answer to question 5 above was yes**, please specify which vermicast products you are currently using on your farm.

Cattle manure	
Sewage sludge	
Vegetable matter	
Others (Please specify)	

Go directly to question 7 if you answered question 6-a

6-b) **If your answer to question 5 was no,** would you be willing to try using vermicast products on your farm?

YES	
NO	

Go directly to question 9 if your answer to question 6-b was no

7) **If your answer to question 6-b was yes**, which of the following vermicast products would you be willing to use on your farm?

Cattle manure	
Sewage sludge	
Vegetable matter	
Others (Please specify)	

8) How much are you currently spending or would you be willing to spend on buying vermicast for use on your farm?

N.B: **Cost below is for five kilograms of vermicast.**

R20-50	
R50-100	
R100-150	
R150-200	

9) Is there anything that concerns you about using vermicast on your farm?

YES	
NO	

10) **If yes**, please provide details?

……
……
……..

11) Do you think that other farmers would be willing to use vermicast on their establishments?

YES	
NO	

Thank you very much for your cooperation