AN ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF THE PROVISION OF RECYCLED WATER IN DURBAN

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Preface

I, Sarushen Dhanapalan Pillay, declare that unless indicated, this thesis is my own work and that it has not been submitted, in whole or in part, for a degree at another university or institution

S.D. Pillay

December 2006

As the candidate's supervisor, I have approved/not approved this thesis for submission

Prof. C.A. Buckley

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My gratitude must also go out to my colleagues at the University of Kwazulu – Natal for providing a stimulating environment that almost made me never want to leave the place.

Rudhren, Derishta, Aroon and Dhesen. Thank you for putting up with my whining and complaining and always pushing me back on the long road ahead. Also to my grandparents whose constant questioning and nagging on why I was taking so long speeded up the process to some extent.

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Lastly and most importantly to my parents Dhana and Krishnee. They bore me, raised me, supported me, taught me and loved me. My gratitude to you knows no bounds.

I dedicate this thesis to the glory of my Guru Sri Swami Sivananda.

Abstract

This dissertation investigated the questions of sustainable development, in the context of water and sanitation provision, for the eThekwini Municipality. The Durban Water Recycling (DWR) plant, run by Veolia Water, was initially the focus of this investigation. The use of recycled water in Durban has freed potable water supplies for a potential 200 000 new consumers. Industry also benefits as the recycled water is supplied at a lower cost.

In order to create a holistic picture of the effect of water recycling, a network incorporating the abstraction, use, re-use and disposal of water in the South Durban Region was investigated. This water supply network was identified consisting of the following units: Inanda Dam, Wiggins Waterworks, the pumping and reticulation network, Durban Southern Wastewater Treatment Works, Durban Water Recycling and the Durban Southern Deep Sea Outfall.

For the environmental analysis the Life Cycle Assessment (LCA) tool was chosen. Life cycle assessment is a systematic way to evaluate the environmental impacts of products or processes by following a scientific methodology in which the impacts are quantified. LCA provides objective answers to environmental questions while suggesting more sustainable forms of production and consumption. It is the only tool which has a cradle-to-grave approach and by this it avoids positive ratings for measurements which only consist in the shifting of burdens. The objective of this LCA was twofold. The first was to quantify and evaluate the environmental performance of relevant processes and so help decision makers choose amongst options. The second objective was to provide a basis for assessing potential improvements in the environmental performance of the system. Once these areas and the contributors to the high burdens were identified, improvement options were investigated. One of the key outcomes of this analysis was the development of an electricity index as an indicator of environmental performance for water and wastewater systems.

The GaBi 3 software package, which uses the CML (Centre for Environmental Science, University of Leiden, The Netherlands) LCA methodology, was used to compile environmental impact scores for each impact category. For the non standard systems such as Inanda Dam and the Durban Southern Deep Sea Outfall a new way of assessing the impacts was developed.

There is an emerging trend to combine the LCA methodology with social issues so as to improve the decision making capability. The social analysis was carried out using an LCA type

methodology. The impact categories selected were; *job creation* and *health and health risks*. During the course of the study the issue of land displacement arose when investigating the social issues surrounding the construction of a dam. This was then incorporated into the entire study.

The system was broken up into sub-systems which were studied separately and then combined to create a holistic picture. Each sub-system was further divided into three stages for analysis; the construction, operation and decommissioning. This method of analysing the system allows for the detailed description of individual process units with the highest social and environmental burden. For example it was identified that the operation of the activated sludge systems at the wastewater treatment works had an environmental burden due to the electricity consumption during this stage. For the impact category of global warming it was discovered that 40% of the total environmental impact of the system could be attributed to the secondary treatment stage at the wastewater works. The construction of the dam had the largest social burden due to the displacement of the communities living in the dam area.

The final part of the study was a scenario analysis. The aim of this analysis was to develop a sustainability framework for municipalities seeking to expand their provision of water and sanitation services. Different scenarios for increasing the water supply of a municipality were considered. The environmental impact of each scenario was also investigated. In this stage various options were considered to see how changes in the system affected the environmental profile. Improvements using new, modified or alternate technologies were suggested and their effects calculated. An operating procedure, for the current system, with the lowest environmental impact was also suggested. The results of this research will prove valuable to designers and planners looking to expand existing water supply networks in a sustainable manner. A sustainability framework was developed to complement the existing DWAF framework for municipalities expanding their provision of water and sanitation services.

The key findings of this study were:

- The quantification of the environmental burdens for the supply of water and sanitation in the eThekwini Municipality first for the individual units then for the system.
- An improvement analysis which suggested ways of reducing the environmental burdens of the existing system.
- The development of a sustainability framework for a municipality to increase its water and sanitation service levels.

- The incorporation of social indicators into the LCA methodology.
- The development of a technique that could be incorporated into the LCA methodology, for assessing the toxicity of complex effluents.
- The development of a method of evaluating the environmental performance of a water and sanitation system using an electricity index.

The thesis provides a holistic view of the abstraction, use, re-use and disposal of water in the eThekwini Municipality and provides a guideline for decision makers when assessing options for expansion or improvement in water supply networks.

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Chapter 1 : Introduction

South Africa is a developing country faced with the challenge of increasing the levels of service of water and sanitation supply. As part of the Government's strategy to alleviate poverty in South Africa a policy for the provision of a free basic level of services has been established. A State of the Nation Address announced that "the provision of free basic amounts of electricity and water to our people will alleviate the plight of the poorest among us" (Mbeki 2001). This led to a new policy to provide 6 000 l of safe water per household per month (Kasrils, 2001). Linked to these policies is also a basic sanitation policy. This requires that a basic level of sanitation, defined as a system for disposing of human excreta, waste water and rubbish which is affordable, easy to maintain and environmentally acceptable, be provided to every household.

Infrastructure for the provision of potable drinking water and the treatment of wastewater is essential for an urban society. South Africa is one of the few countries in the world that recognises water as a basic human right. Approximately half the world's population is now living in cities and the percentage is increasing, especially in the developing world (Lundin, 1999). Urbanisation concentrates people and increases the demand for food, water, goods, waste management and means of transportation. The cost is an increasing pressure on the environment and its surroundings.

Concern with both the detrimental health effects and environmental impacts of sub-optimal management of waste and increasing levels of pollution in South Africa has escalated recently. The situation in South Africa, exacerbated by the apartheid legacy, has yet to be rectified. In particular the inequitable proportion of the pollution burden borne by previously disempowered communities has to be redressed (DEAT, 1997).

Section 24 of the Bill of Rights in the Constitution of the Republic of South Africa guarantees environmental rights for the people of South Africa.

Section 24 states that "Everyone has the right -

- to an environment that is not harmful to their health or well-being; and
- to have the environment protected for the benefit of present and future generations, through reasonable legislative and other measures that prevent pollution and ecological degradation; promote conservation; and secure ecologically sustainable development

> and use of natural resources while promoting justifiable economic and social development."

At the UN Millennium Assembly in 2000 and the World Summit on Sustainable Development (WSSD) in 2002 a number of commitments were made regarding the provision of water and sanitation services. These commitments are summarised in Table 1-1.

Table 1-1: A summary of the Millennium Development Goals (MDG's) agreed at the UN Millennium Assembly and the commitments made at the WSSD summit in Johannesburg.

Drinking Water

MDG: halve the proportion of people without sustainable access to safe drinking water by 2015

WSSD: states agreed to launch a program of action; with financial and technical assistance to achieve the MDG on safe drinking water

Sanitation

MDG: sanitation was not mentioned as a goal but is seen as part of achieving the *significant improvement in the lives of at least 100 million slum dwellers*

WSSD: all governments agreed to a new target to halve the proportion of people without access to basic adequate sanitation by 2015 which includes actions to:

- develop and implement efficient household sanitation systems
- improve sanitation in public institutions, especially schools
- promote safe hygiene practices
- promote education and outreach focused on children
- promote affordable and socially and culturally acceptable technologies and practices
- develop innovative financing and partnership mechanisms
- integrate sanitation into water resources management strategies

these were agreed at the summit in Johannesburg and are now being treated as an MDG

Integrated Water Resource Management Plans

WSSD: all governments confirmed they would develop plans for integrated water resource management and water efficiency by 2005 with support to developing countries

South Africa is committed to achieving these goals. At the present rate of delivery the government is on track to not only meet the WSSD targets for reducing the percentage of people without access to basic water and sanitation, but also to eradicate the backlog of infrastructure for water by 2008 and sanitation by 2010 (van Schalkwyk, 2004).

As one of the fastest developing countries in Africa, South Africa is faced with an additional problem. It is thought that a relationship exists between the income per capita and the rate of environmental degradation. This is known as the environmental Kuznet's curve, a term coined by Seldon and Song (1994) based on the work of economist Simon Kuznet. The theory states that as the per capita income increase so to does the rate of environmental degradation. The shape of the relationship between income and degradation is that of an inverted 'U' . The inverted-U shaped environmental Kuznet's curve is thought to capture the progression towards ever-higher income per capita, which is initially associated with an increase in the rate of environmental degradation but then, after a turning point, the rate of environmental degradation decreases. The problem facing many cities in South Africa is to provide increased water and sanitation services without causing increased environmental degradation, and to be able to do this in a sustainable manner.

Sustainable development is commonly defined as *development which meets the needs of the present generation without compromising the ability of future generations to meet their own needs* (WCED, 1987).South Africa is located in a predominantly semi-arid part of the world. The climate varies from desert and semi-desert in the west to sub-humid along the eastern coastal area, with an average rainfall for the country of about 450 mm/y, well below the world average of about 860 mm/y, while evaporation is comparatively high (DWAF, 2004). As a result, South Africa's water resources are, in global terms, scarce and extremely limited. With an increasing population and a backlog in the provision of water and sanitation services the challenge facing municipalities is how to increase the water and sanitation service levels while reducing or maintaining abstraction levels and doing this in a sustainable manner.

The question that this thesis answers is, *how to increase the water and sanitation levels of a city in a manner that causes the least environmental and social impact.* However, in order to propose methods of increasing the service levels one must first understand the current levels of service.

The eThekwini Municipality was used as the case study that formed the basis of this thesis. This municipality is regarded as one of the best run in the country regarding the provision of water and sanitation services and is renowned for their innovative approach to tackling the challenge of providing increased water and sanitation services having won the Dubai International Award for Best Practices in 2003 and two Impumelelo Innovation Awards (1999, 2005).

The study was prompted by the introduction of a water recycling scheme to recycle sewage to provide water for industrial use. This was the first recycling scheme of its kind in the country. The initial aim was to determine whether the recycling benefited the city, if at all, environmentally. In order to assess the magnitude of the environmental burdens it was decided to use the environmental life cycle assessment (LCA) tool. LCA is a systematic way to evaluate the environmental impacts of products or processes by following a scientific methodology in which the impacts are quantified. What started as an LCA of a single process was soon expanded once the complex nature of the water pathways was understood. Initially the study was intended to be a gate-to-gate LCA of the water recycling plant. However it soon became clear that the impacts of recycling could not be considered in isolation without considering the downstream effects of a more concentrated effluent or the upstream effects of reduced potable water production. It was therefore decided to consider a water supply network starting at Inanda dam and ending at the eThekwini Southern Wastewater Treatment Works deep sea outfall in the system boundary.

It was also found that by reducing the study to an LCA of the system many of the important social impacts would be ignored. Hence it was decided to also include a social analysis in order to create a more holistic picture of the impacts of the system.

1.1. Tools used

Three tools were used for the purposes of this study. Of these the first two, LCA and social analysis, were used to quantify the burdens of the existing system. The third, scenario analysis, looks at how changes to the system affect the environmental performance of the system.

1.1.1. Life Cycle Analysis

There are many tools available for performing an environmental evaluation of a product, process or system. A comparison of some of the more popular tools is presented in Table 1-2.

Table 1-2: Comparison of selected environmental tools

	Environmental Impact Assessment (EIA)	**Environmental Risk Assessment (ERA)**	**Life Cycle Assessment (LCA)**
Purpose	Identifies and predicts the environmental impacts of a project, policy or similar initiative; provides basis for decision on acceptability of likely impacts	Risks to the environment and public health are estimated and compared in order to determine the environmental consequences of the initiative under consideration	Evaluates the environmental burdens associated with a product, process or activity, explicitly over the entire life cycle

For the purposes of this study the LCA tool was used. LCA is a systematic way to evaluate the environmental impact of products or processes by following a cradle-to-grave approach. LCA is the process of evaluating the effects that a product has on the environment over the entire period of its life cycle. It can be used through product design and process selection, to purchasing decisions and final disposal routes. LCA provides objective answers to environmental questions while suggesting more sustainable forms of production and consumption. It uses a scientific approach in which the environmental impacts due to a product or activity are quantified. It is the only tool that has a cradle-to-grave approach and by this it avoids positive ratings for measurements which only consist in the shifting of burdens (Kloepffer, 1997)

1.1.2. Social Analysis

Social impacts are the impacts of a project, plan, programme or policy on people. Social impact assessment is an integral part an environmental assessment report and is mandatory in some countries. The social impacts for this study were evaluated using a life cycle assessment type methodology where all the inputs and outputs were considered and evaluated using a judgement method. Two impact categories, common to all process units, were identified for use as indicators for this study. These are *job creation* and *health and health risks*. The impact category of *job creation* relates to the creation of direct and indirect jobs. *Health and health risks* relate to the number of injuries and the effect on human health of an activity. The social indicators were calculated using a judgement based method.

1.1.3. Scenario Analysis

In order to model the scenarios a systems approach was used. This approach, as defined by Emery (1969), is a way of considering phenomena or objects as a whole. Thus each scenario was evaluated as an entire system. This allows for one to gain a complete understanding of the system.

Systems thinking involves a hierarchical understanding of systems within systems (Kay and Foster, 1999). Systems thinking is fundamentally different from more conventional ‘scientific thinking’ as conventional scientific understandings and methods are reductionist while systems thinking incorporates reductionist understandings but is holistic (Bell and Morse, 1999).

Two scenarios were considered. Both scenarios consider an increase of 200 000 new customers to the eThekwini Municipality’s water and sanitation network. The first scenario, Scenario A, considers the case where the new customers are in an urban environment such as Cato Manor township. Scenario B considers the case where the new customers are in a rural environment. The difference between the two scenarios is the type of sanitation used.

1.2. Aims and objectives

The main aim of this study is to generate information on the environmental life cycle of water in an urban context. This includes the abstraction and treatment of raw water, the distribution of potable water, the collection and treatment of wastewater, the disposal to sea of effluents and the recycling of water. Of particular interest was the environmental efficiency of recycling water for industrial use. Using this information this thesis will attempt to answer the following 'key questions';

What is the environmental and social cost of the provision of expanded water and sanitation services in the eThekwini Municipality? It has been hypothesised that LCA is an appropriate tool to answer this question. Using the LCA methodology the environmental cost will be evaluated. An LCA type methodology will be used to evaluate the social cost.

What are the main contributors to these burdens? One of the uses of LCA is as a focussing tool. Therefore a cradle-to grave LCA of each unit in the system is anticipated to reveal hotspots. It was with this in mind that each unit was analysed separately before examining the system as a whole.

Are there ways of reducing this load and if so by how much? The improvement analysis section of the LCA will examine this by targeting the units with a high environmental load. The effect of modifications and process changes will be examined.

How can the water and sanitation service levels be increased in a sustainable manner?

What is the most environmentally efficient way of doing this? The scenario analyses that are carried out in Chapter 6 will attempt to answer this question by considering an increase of 200 000 new customers in the eThekwini Municipal region. The results from this will then be extrapolated to other municipalities in South Africa.

What is the net effect of providing recycled water in Durban? Is this the best way of increasing the water supply?

This is the question that initially prompted this study. In order to provide the answer to this question a base case will be modelled (in Chapter 6) which describes the eThekwini Municipality before the construction of the recycling plant. The recycling plant will then be introduced to this model in order to assess its impact.

The current decision making framework for South African municipalities seeking to increase the water and sanitation provision levels (see next page) takes only three variables into account for decision making (DWAF, 2006). These are availability of water resources, water demand and affordability. The important issue of sustainable development is not addressed. One of the key aims of this thesis is to develop a fourth decision making framework based on sustainability criteria. This sustainability framework will complement the existing decision making framework.

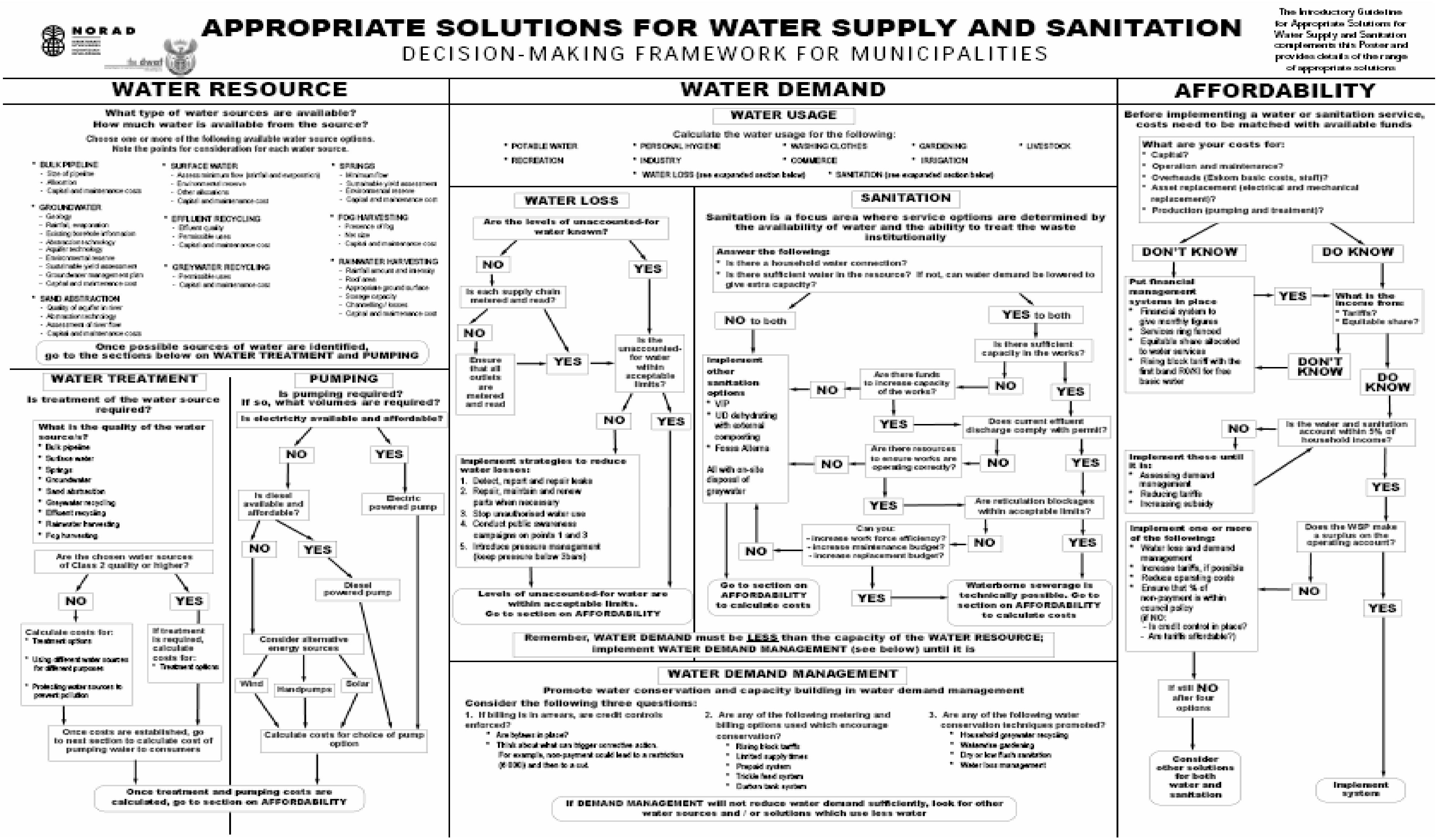

Figure 1-1: The existing decision making framework for municipalities in South Africa. One of the aims of this thesis is the development of a fourth column which considers sustainability criteria.

1.3. Thesis Structure

This thesis is divided into six chapters, with each chapter dealing with a specific objective. Each chapter is self contained. This means that the chapters can be read independently of each other with all the literature pertaining to the chapter and a list of references included in each chapter.

The thesis starts with a description of the studied system in **Chapter 2**. All relevant information about each of the sub-systems is included. **Chapter 3** uses this information to perform a detailed LCA of the system. In this chapter the environmental burdens of the system are quantified. Adopting a similar methodology **Chapter 4** examines the social burden of the system. One of the key findings of the environmental and social analysis was the large contribution of the use of electricity to the burdens. **Chapter 5** is a study on the impact of power generation in South Africa. Using the results from the previous chapters, **Chapter 6** uses a technique called scenario analysis to present alternate methods of water supply and sanitation and examines the associated environmental impacts.

Chapter 2 presents a description of the studied system. The system boundaries are explained and the assumptions for defining these explained. In order to understand the environmental and social assessments a detailed description of each sub-system is required. The chapter is divided into six sections, each a sub-system in the system network. Each section contains background information about the unit being described as well as detailed information regarding the operation of the unit. The chapter opens with Section 2-1 which looks at the construction and operation of Inanda dam. Sections 2-2 and 2-3 examine the production and use of potable water in the selected system pathway. Section 2-4 presents the treatment of the effluent and Section 2-5 the recycling of this effluent. Section 2-6 covers the disposal of the waste sludge and the residuals that are not recycled.

In **Chapter 3** the LCA of the system is presented. This chapter presents a brief explanation of each stage of the LCA methodology as well as the results from each stage. Hypothesis and assumptions are stated before the results are presented. A discussion of the results concludes each section. Section 3-1 presents the goal and scope of the study. Here the system boundaries of each sub-system are identified and the chosen functional unit explained. The inventory analysis stage of the LCA is discussed in Section 3-2. Section 3-3 deals with the impact assessment stage. The impact models and methods used to calculate the environmental loads are discussed here. The chapter concludes with the final stage of an LCA the interpretation phase in Section 3-4.

This chapter ends with a discussion in which the validity of the assumptions is checked. The key findings that the LCA has highlighted are presented.

Chapter 4 presents the social analysis of the system. The chapter opens with Section 4-1 where the historical background of social impact analysis is discussed. Here the different types of social analysis are presented and the link between social impact analysis and LCA is examined. Section 4-2 continues with the theory and methodology chosen for this particular study. Here mention must be made that the aim of this study is not to provide an in-depth social analysis but rather to present some of the social impacts so that a holistic picture can be created when examining the system and each sub-system. The results are presented in Section 4-3 and the chapter concludes with a discussion of these results.

There are data that are common in all LCIs, namely electricity, transportation and waste management. Electricity use, especially, features very prominently in the total LCA results for the majority of product life cycles. Thus a detailed analysis of the electricity generation methods and their impacts is presented in **Chapter 5**. In this chapter Section 5-1 presents a review of the electricity generation process in South Africa and compare this with the electricity impact model used. The impact model used was developed by the Centre for Environmental Studies at the University of Leiden and this model is presented in Section 5-2. This model is based on European coal fired power stations. Section 5-3 examines the environmental impact of power generation in South Africa and the inventory for the impact model used is compared to an inventory for South African coal based power generation. In Section 5-4 the social impacts of coal based power generation are considered. As South Africa is looking to increase its power generation ability Section 5-5 examines alternate methods of power generation and the associated environmental and social impacts.

Different scenarios for increasing the water supply of a municipality are discussed in **Chapter 6**. The environmental impact of each scenario is also investigated. This chapter opens with a brief description of the scenario analysis methodology in Section 6-1. The assumptions are stated and the different scenarios considered are presented. Section 6-2 considers the base case which considers the status quo. Before changes or modifications can be made for other scenarios one must ask whether the current system is operating efficiently and if not what can be improved. This is examined in an improvement analysis in Section 6-2-2. This analysis suggests changes to the way the system is operated to give a better environmental performance. Section 6-3, 6-4 and 6-5 examine the other options that have been considered. The chapter ends with a discussion in

Section 6-6 where the results and insights that have been gained are expanded to consider three hypothetical municipalities facing water shortages.

The appendices have been prepared in a similar fashion each a standalone chapter. Additional information is presented that while useful, is not vital to the flow of this thesis. **Appendix 1** examines the abstraction and storage of water in Inanda dam. The additional impacts that are not covered by the LCA methodology are discussed and the assumptions made when calculating the dam's environmental scores are presented in greater detail. The method that was developed for measuring the ecotoxicity of the sludge going to sea is explained in **Appendix 2.** In **Appendix 3** more information on the urine diversion toilet is presented. This is the method of on-site sanitation chosen by the eThekwini Municipality and is discussed in the scenario analysis in **Chapter 6.** The environmental burdens of this method are also presented in this appendix. With LCA being a data intensive process, it is important to assess the quality of the data used in order to assess the quality of the results. The data quality is evaluated using a methodology developed by Weidema (1997) in **Appendix 4. Appendix 5** presents the raw inventory data that was collected and used for the LCA.

1.4. References

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Chapter 2 : System Boundaries and System Description

This chapter outlines the system that was studied. As required in the first part of any life cycle assessment the system boundaries first need to be identified. These are presented along with all assumptions that were made.

The system under investigation is a complex water supply network. The nature of these networks do not allow for easy identification of a single chain of water supply. Networks are often inter-linked with one network drawing from or supplying other networks. This is particularly evident in the eThekwini Municipality where different dams are used to supply different treatment works depending on rainfall conditions. The major dams used to supply water to the Durban region are the Midmar, Albert Falls, Nagle, Inanda and Hazelmere dams. A hypothetical system was created to represent a water supply chain.

Figure 2-1 presents a map showing the major dams used to supply the eThekwini Municipality.

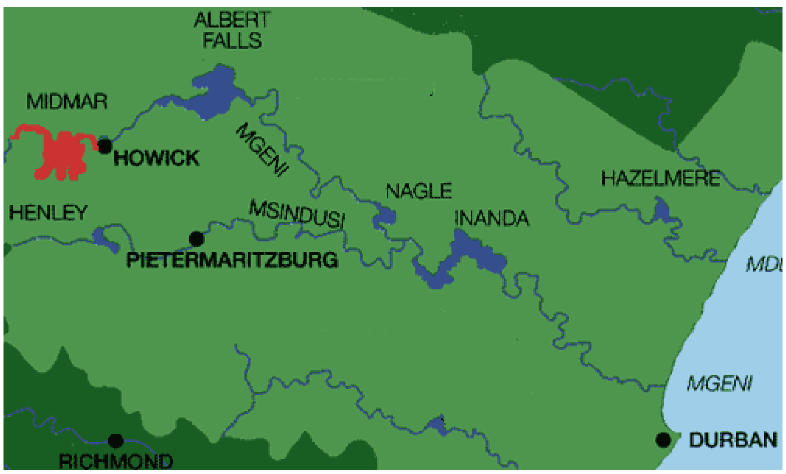

Figure 2-1: Map showing the region of study with the major dams and rivers supplying the eThekwini Municipality indicated

The selected system for this study starts at Inanda Dam just outside the boundaries of the eThekwini Municipality. Water from this dam feeds the Wiggins Water Treatment Works. This treatment works has a capacity of 350 Ml/day and is used to supply water to the south Durban region. A problem was encountered when identifying a pumping and piping network as it is possible to supply this region from more than one waterworks. The pumping and piping network is operated to reduce the electricity usage of the city. Therefore under normal operating conditions the bulk of the flow is via gravity.

Wastewater collected from the region is sent to the Southern Wastewater Treatment Works. This works receives a combination of domestic sewage and industrial effluent. The bulk of the industrial sewage receives little treatment before being sent to the deep sea outfall. The domestic wastewater is treated before being pumped to the Durban Water Recycling Plant. This plant treats the sewage to an acceptable standard for industrial use. The water is then pumped to a high level storage tank before being distributed to nearby industries.

The industrial waste is sent through a system of screens, degritters and settling tanks before being sent to the deep sea outfall. This is a 4 km long pipeline which goes out to sea and discharges the waste at a depth of 60 m.

Figure 2-2 presents a simplified description of the selected water system.

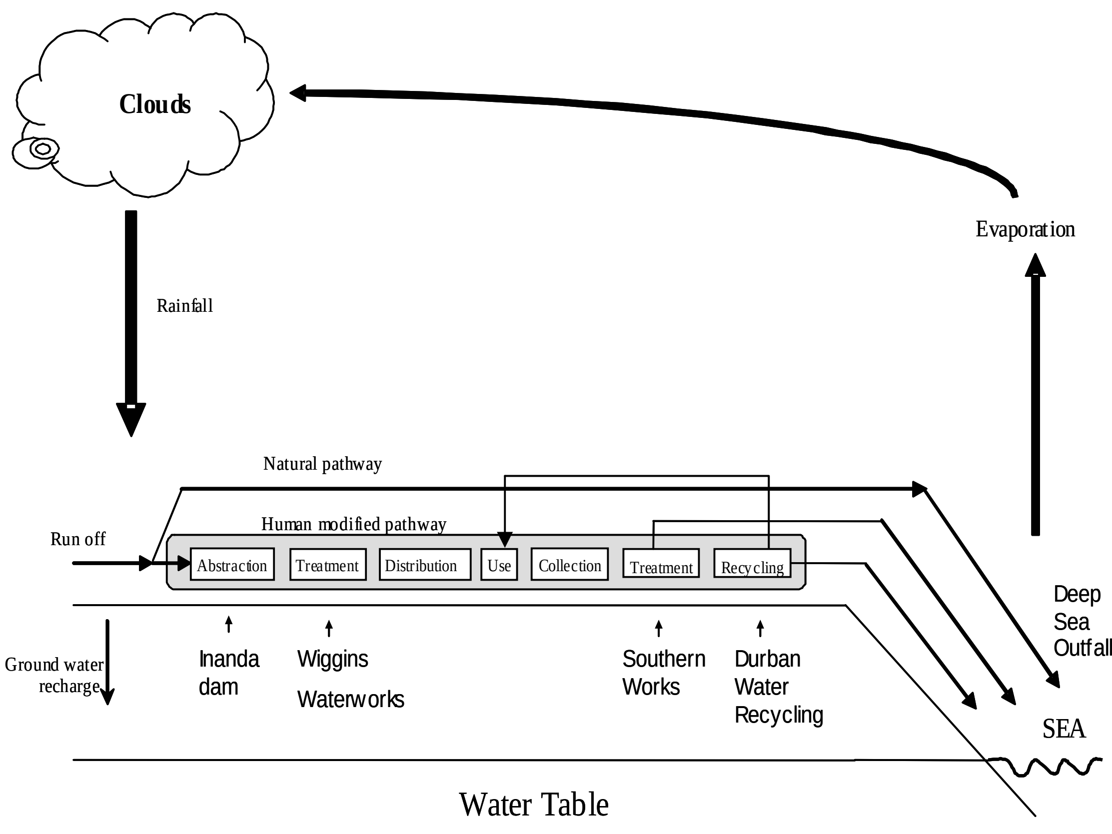

Figure 2-2 Simplified description of the selected water pathway showing both the natural water pathway and the human modified pathway.

In order to understand the environmental and social impact assessments a detailed system description is required. This chapter is divided into six sections, each a sub-system in the system network, and provides this detailed description. Each section contains background information about the unit being described as well as detailed information regarding the operation of the unit. The chapter opens with Section 2-1 which looks at the construction and operation of Inanda Dam. Sections 2-2 and 2-3 examine the production and use of potable water in the selected system pathway. Section 2-4 presents the treatment of the effluent and Section 2-5 the recycling of this effluent. Section 2-6 covers the disposal of the waste sludges and the residuals that are not recycled.

2.1. Inanda Dam

Inanda Dam was constructed in 1989 amid much controversy. This was a period during the apartheid era in South Africa and the situating of the dam in the midst of a tribal area in an 'independent' homeland was regarded with hostility by the local community. The protests and forced removals associated with the dam along with the other social impacts are presented in Chapter 4 which examines the social impact analysis of the system. This section covers the technical aspects of the dam's construction and operation.

Figure 2-3 Photograph showing the dam wall of Inanda Dam

Inanda Dam has a concrete wall with an earth embankment design. This is shown in Figure 2-3. The dam is fed from a catchment area of 4 082 km^2. The total capacity of Inanda Dam is 251 746 $10^6 m^3$ and the dam has a surface area of 14.63 km^2. The dam has an ‘S’ shape. Entering water has a residence time of approximately two years (Terry, 2004). The maximum daily abstraction capacity of the dam is 300 Ml/d although the dam currently produces about 200 Ml/d. The main river entering the dam is the Umgeni river, the dam is situated 32 km inland of the river mouth (Garland, 2000). Appendix one contains a more detailed description of Inanda Dam.

2.2. Wiggins Waterworks

Wiggins Waterworks is situated in the eThekwini Municipal region in the area of Wiggins. This waterworks was commissioned in August 1984 and it supplies water to the Durban region. The initial capacity was 175 Ml/d and in 1995 following an expansion this was raised to 350 Ml/d. A system of tunnels and pipelines supplies the raw water from the Inanda Dam and gravity is used for the transportation of the incoming water. The waterworks is situated 110 m above sea level and the treated water flows by gravity (Rodrigues, 1992) to the municipal reservoirs. The purified water is purchased in bulk from Umgeni Water and distributed by the eThekwini Municipality.

Figure 2-4 presents a simplified process flow diagram of the waterworks. The plant uses a conventional treatment process with pre-ozonation, chemical addition, clarification, deep bed filtration and chlorination.

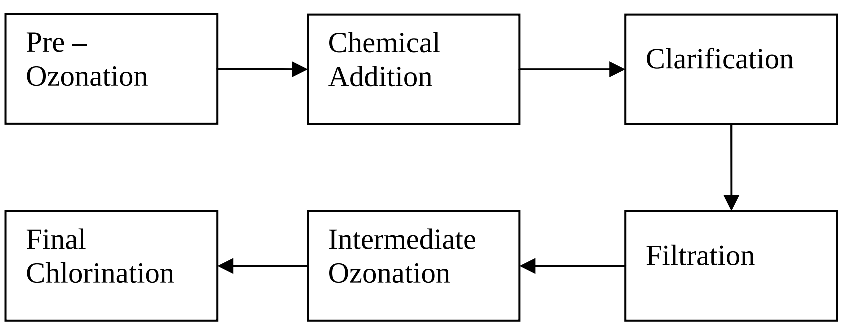

Figure 2-4 Simplified process description of Wiggins Waterworks

A detailed description of each process unit is now presented. The information for this description is taken largely from the Umgeni Water Public Affairs Department (1998) and the Master's thesis of Elena Friedrich (2001).

2.2.1. Pre - Ozonation

Ozone is produced on the premises by three 30 kg/h Trailigaz ozonators. The ozonators use a liquid oxygen feed and the ozone produced is dosed at two points in the waterworks. Four pre-ozonation tanks are situated at the head of the works before chemical addition. The pre-ozonation tanks are fitted with static mixers at their inlets. The mixers diffuse the ozone into the water enhancing the mixing process. A thermal destruction unit (TDU) is fitted to the gas outlet of each ozonation unit. The gases exiting the ozone contactor are heated to 380 ^{o}C to decompose the poisonous ozone gas. The generation and destruction of ozone and the ozone concentration in the contact tanks is monitored and controlled by an array of in-line meters.

Pre-ozonation at Wiggins Waterworks is used mainly for the oxidation of iron, manganese, trihalogented methane (THM) precursors and taste and odour compounds such as geosmin and 2-methylisoborneol. It also helps in removing algae, improving the colour of the final water and reducing coagulant demand.

2.2.2. Chemical dosing

Following the pre-ozonation process chemicals are dosed to the water. A description of the chemicals added and their function follows;

Powdered activated carbon is used intermittently depending on the quality of the incoming water. It is used for taste and odour control.

Pre-chlorination is the next step in the treatment of water. There are facilities for the addition of chlorine and sodium hypochlorite. These chemicals are generated on-site. They are used for the disinfection of water and the prevention of growth in the subsequent plant.

HTH (calcium hypochlorite) is also occasionally used for disinfection. It is mainly used for the disinfection of tanks after maintenance works.

Slaked lime is used for pH control, and as with chlorine, is used throughout the year in the treatment of water. The lime is dosed before the polymeric coagulant since the effectiveness of the coagulant is pH dependent.

Polymeric coagulant consists of a blend of cationic polyamines, polydiallyldimethylammonium chloride (polyDADMAC) and some inorganic components.

Bentonite is used as a coagulant aid because of its property to expand thereby increasing the size, density and strength of the flocs formed.

2.2.3. Clarifiers

There are four Degremont sludge blanket pulsator type clarifiers at Wiggins Waterworks (Thompson, 2000). The surface area of each clarifier is 995 m^2 and they allow for a rise rate of 4 m/h at a flow rate of 350 Ml/d with a retention time of 1.09 h. The raw water enters the clarifier tanks through a series of perforated pipes situated near the bottom of each tank. Some of the incoming raw water is induced into two vacuum chambers. The vacuum causes the level of the raw water to rise in the vacuum chamber to about 0.6 to 1 m above the level of the water in the clarifier tanks. On reaching this an air inlet valve is opened automatically and the water in the vacuum chamber is exposed to atmospheric pressure. This causes the raw water to flow back into the clarifier. This design facilitates flocculation by promoting collision of the flocs in the raw water and larger flocs that have already formed.

Stilling plates are situated above the perforated pipes so that the entering water rises uniformly, allowing settlement of the coagulated particles (or flocs) and the formation of a sludge blanket at the bottom of each chamber. At the top of each tank a set of perforated channels collect the clarified water, evenly and without any velocity disturbances to the other layers of the tank. The clarified water is then directed to the filtration unit (Thompson, 2000).

During the settling process a sludge layer is formed at the bottom of the clarifier tanks and the sludge then overflows into hoppers. The sludge blanket depth is about 2 m and as the sludge reaches a concentration of 0.3% solids, it is automatically discharged into a homogenization tank.

2.2.4. Filtration

There are 24 Degremont Aquazur “V” type gravity filters that make up the filtration unit at Wiggins Waterworks (Thompson, 2000). Two cells make up each filter and each cell has a surface area of 56 m^2. The filters are designed for a maximum filtration rate of 6 m/h. The filter has a suspended floor/nozzle system. The depth of filter sand in the filter is 900 mm and the effective grain size is 0.95 to 1.35 mm. The water depth above the filter media ranges from 1.0 to 1.2 m depending on the flowrate and the condition of the filter.

During the filtration process suspended particles penetrate the media and are captured some distance below the media surface (van Duuren, 1997). To maintain efficiency of filtration in this type of system, backwash is needed at regular intervals. A characteristic of this type of filter is the simultaneous air scour and backwash accompanied by surface sweep, followed by a water rinse of the filter during backwash.

The backwash water is collected in a wash water recovery tank after it has passed a sand trap, which collects the sand which was washed out with the wash water. After settling, the resulting sludge is pumped to the waste sludge homogenisation tank and the recovered water is returned to the raw water stream just after the addition point of polymeric coagulant.

2.2.5. Intermediate ozonation

Intermediate ozonation is carried out after filtration and the aim of this operation is disinfection. The process occurs in two intermediate ozonation contact tanks where the ozone/oxygen mixture is introduced at the bottom of the tanks through porous carborundum diffusers. To ensure that unreacted ozone which has not dissolved in the water does not enter the environment, a thermal destruct unit accompanies the intermediate ozonation unit. The destruction unit is similar in design to the one employed in the pre-ozonation process.

2.2.6. Final chlorination

Final chlorination is used after intermediate ozonation and just prior to the treated water entering the storage tanks. At this point there are facilities for dosing chlorine and sodium hypochlorite. The aim of this operation is to disinfect the water and to introduce a residual chlorine dose in the treated water in order to prevent re-inoculation with pathogens during storage and reticulation. The average chlorine residual in the reservoir tanks is about 0.5 mg/l.

2.2.7. Sludge Treatment

The waste sludge homogenization tank is fed with sludge from the clarifiers and wash water recovery tanks. From the homogenization tank the sludge may follow one of two routes prior to disposal. In the first the sludge is pumped to a dissolved air flotation (DAF) unit. This unit uses ‘air pressurised’ water (i.e. water in which air has been dissolved under high pressure) to create micro bubbles which rise through the incoming sludge. Small particles of sludge adhere to the micro bubbles and are transported to the surface from where they are continuously removed. These floating scrapings are directed to the thickened sludge sump. Larger and heavier particles in the sludge settle to the bottom of the DAF unit. This settled sludge is scraped continuously and also pumped to the thickened sludge sump. The water from the DAF is pumped to the wash recovery tanks where it is mixed with the filtration wash water and follows the same recycle path.

In the second route, sludge from the homogenization tank is passed through a gravity thickener. From the thickened sludge tank the sludge can be either diluted and disposed of into the municipal sewer during off peak periods (this method is employed most of the time), or it is passed through centrifuges and further concentrated. The sludge has to be diluted to a solids concentration of 1% for disposal to the municipal sewer. The cake resulting from centrifugation has a solid concentration of about 25 to 30% and it is disposed to a landfill site. The water recovered through centrifugation is pumped to the wash water recovery tanks and recycled.

2.3. Pumping and reticulation network

The distribution of potable water in the eThekwini Municipality is the responsibility of both the eThekwini Municipality (ETM) and Umgeni Water. The potable water is transported from Wiggins Waterworks to the municipality reservoirs by gravity flow. From these reservoirs 107 pumping stations throughout the municipality then distribute the potable water. As stated previously, the distribution networks are complex and thus it was decided to use average figures for the entire eThekwini Municipality when calculating the specific material and energy consumption. If one takes into account that there is a loss of 30% in the distribution system (eThekwini Municipality Wastewater Services Report), the energy figures are calculated as 0.13 kWh/kl of potable water delivered to customers.

The collection of wastewater is the responsibility of the ETM. Considerable pumping is required to direct the wastewater streams to the treatment plants. An average figure of 0.14 kWh/kl was obtained (Friedrich et al., 2005) for the collection of wastewater in the ETM. This excludes the stormwater which enters the sewer network which comprises about 6 percent of the total annual flow.

2.4. Southern Wastewater Treatment Works

The Southern Wastewater Treatment Works is situated in Merebank, Durban. This works was commissioned in 1969 and treats 168 Ml/day. This represents 36% of the eThekwini wastewater treatment capacity (Howarth, 2005). It receives domestic sewage from the areas of Chatsworth and Merebank (Chatsworth sewer line) and industrial effluents from the surrounding industries (Mobeni sewer line). There is a reception station for tankers. For the purposes of this study the plant was divided into a primary and secondary treatment section. The primary section comprises the screens, degritters and primary settlers. The secondary section is made up of the activated sludge and clarification units. It was suspected that the secondary treatment is responsible for a large proportion of the impacts and thus was examined in great detail in order to suggest improvements.

Sewage entering the works has two possible routes. The first is to go through primary treatment before being sent to sea via the deep sea outfall. The second route is for the sewage to pass through the primary, then secondary treatment before being sent to the Durban Water Recycling plant for tertiary treatment. The heavy industrial effluents take the first route and the light industrial effluent and domestic sewage take the second route. This study considers the second route.

The treatment processes employed in the wastewater treatment plant are as follows; screening, degritting, sedimentation, activated sludge treatment and clarification.

2.4.1. Primary Treatment

This study has broken the primary treatment section of the works into five units for analysis. Figure 2-5 shows this breakdown.

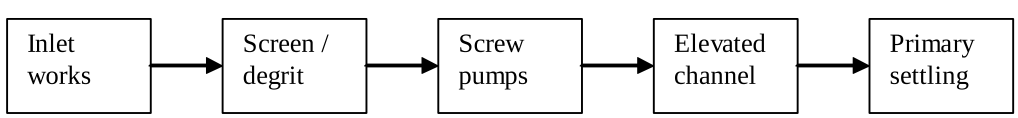

Figure 2-5 Block diagram of the primary treatment section of the Southern Wastewater Treatment Works.

Raw sewage enters the head of works where it is sent to the coarse screens and the degritting channel. The screw pumps then raise the sewage to an elevated channel from where it is sent to the primary settling tanks. The inlet of the works and the elevated channel were included as separate units due to the large amount of concrete used in their construction.

2.4.1.1. Inlet Works

A large grating is present at the head of the works. This is to remove large objects that have made their way into the sewer system such as large stones, plastic bags and bottles, pieces of vegetation and the like. The head of works is a concrete channel into which the different sewer lines feed.

2.4.1.2. Screening/Degritting

Screening is used to remove the gross pollutants from the wastewater. Coarse screens are used as the first treatment unit for the primary purpose of protecting plant equipment against reduced operating efficiency or physical damage (WPCF, 1977).

The inert fraction of settlable solids in municipal wastewater consisting of ashes, clinker, sand particles etc is termed grit. If not removed in primary treatment, grit in primary settling tanks can cause abnormal abrasive wear on mechanical equipment and sludge pumps, can clog pipes by deposition and can accumulate in sludge holding tanks. The grit removal units are designed to remove particles equivalent to fine sand, defined as 0.2 mm diameter particles with a specific gravity of 2.7. Grit settling is carried out in a channel type grit chamber.

The separated screenings and grit are collected and sent to a landfill site.

2.4.1.3. Screw pumps

There are two screw pumps at the Southern Wastewater Works, which are used to lift the incoming sewage into an elevated channel which supplies the primary settlers. The screw pump is a rotating helix conveyor that pushes wastewater up an inclined trough to a higher elevation. Screw pumps are used primarily for low lift, high capacity, and non-clog pumping operations. Operating characteristics are such that the head remains constant, decreasing slightly as the fluid level at the inlet to the screw pump rises. Pumping and power demand increase automatically with the rise of the fluid level at the inlet, while the pump rotates at a low constant speed (WPCF,1977).

The efficiency of the screw pumps increases from the minimum flow capacity to the rated capacity. Near maximum efficiency is produced across the entire top 70 to 80% of the pumping range. These units are suited for variable capacity operation, because the fluid level at the inlet of the screw controls the rate of discharge. Power varies almost directly with the pumping rate, resulting in higher efficiencies over a larger variety of pumping capacity.

The screw pump consists of two leads of steel flighting welded around a watertight steel tube. A trough of steel or concrete is provided for conveying of the liquid and entrained solids. The screw is driven by a motor through a speed reducer at the top of the unit. The bottom of the screw is immersed in the inflow channel. Screw pumps require no wet well or suction and discharge piping. This unit is used for lift of wastewater into the primary settlers.

2.4.1.4. Primary settling

The primary settling basins are used to remove the readily settlable solids ahead of subsequent treatment. The settlable solids in municipal sewage and many organic industrial wastewaters include flocculated and discrete settling particles. The settlers operate on the principal that when wastewater, containing a suspension of solid particles that have a higher specific gravity than the liquid, is in a quiescent state, the particles will settle out because of gravity. This gravity settling is the method by which most suspended matter is removed from wastewater during the course of treatment (WPCF, 1977).

2.4.2. Secondary treatment

The secondary treatment plant consists of only two units, an activated sludge unit followed by four clarifiers. The overflow from the primary settlers enters the activated sludge unit where it is aerated and broken down by bacteria. The activated sludge then flows to the clarifiers where the sludge settles. The clarified effluent flows to the tertiary treatment plant. Some of the sludge is recycled to the activated sludge unit and the balance is sent to a deep sea outfall pipeline. Figure 2-6 shows a block diagram describing the secondary treatment process.

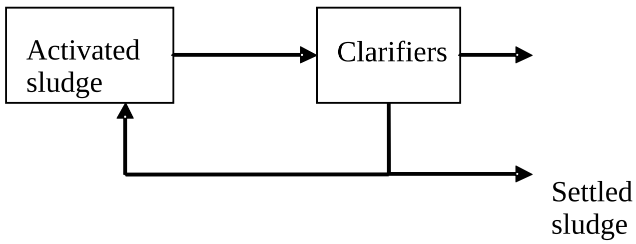

Figure 2-6: Block diagram showing of the secondary treatment section of the Southern Wastewater Treatment Works.

The secondary treatment plant was set up with the express purpose of supplying the tertiary treatment plant. The plant has an operation capacity of 50 Ml/d with peak flows of 77.4 Ml/d. (IMIESA, May 1999)

The activated sludge and the clarifiers will be dealt with in greater detail than the other units in the primary and tertiary treatment plants as it is suspected that this is an area where large environmental improvements can be made.

2.4.2.1. Activated sludge

The activated sludge process is of conventional design and serves to remove 95% of the incoming COD and 98% of the incoming ammonia loads. The process is operated in the nitrogen removal mode with typical effluent nitrate and nitrite concentrations of 5 mg/l and 0.02 mg/l respectively. Typical effluent COD and ammonia concentrations are 15 mg/l and 0.2 mg/l respectively.

The 12 surface aerators are able to introduce 992 kg O_2/h into the mixed liquor during the peak flow period. The pH of the entering influent is continuously monitored to prevent acidic effluent entering the aeration tanks. Upon detection of a pH less than 4 a motorised penstock automatically closes and by-passes the effluent to the waste sludge line.

Activated sludge is defined as a suspension of microorganisms, both living and dead, in a wastewater. The microorganisms are activated by an input of air (oxygen). The influent to the process is usually settled. The process involves two distinct operations usually performed in two separate basins: aeration and settling.

Raw wastewater flowing into the aeration basin contains organic matter (COD) as a food supply. Bacteria metabolise the waste solids, producing new growth whilst taking in dissolved oxygen and releasing carbon dioxide. Protozoa graze on bacteria for energy to reproduce. Waste organics are incorporated into the biological floc by bacterial synthesis and predatory protozoa.

The liquid suspension of microorganisms in an aeration basin is generally referred to as mixed liquor, and the biological growths are called mixed liquor suspended solids. Mixed liquor is continuously transferred to a clarifier for gravity separation of the biological floc and discharge of the clarified effluent. Settled floc is returned continuously to the aeration basin for mixing with entering raw water.

Oxygen, which is usually supplied by aeration, must be input continuously or semi continuously. This is the major energy consuming operation in the process.

At higher sludge ages and longer detention times a typical activated sludge process will produce a nitrified effluent. Denitrification occurs when certain microorganisms in an environment devoid of oxygen use nitrate as an electron acceptor to oxidize organic matter. Nitrate is reduced to nitrogen gas. The reactions describing nitrogen transformations in sewage treatment are as follows:

$$\text{Organic matter} + O_2 \rightarrow NH_3 + \text{microorganisms} + CO_2$$

$$NH_3 + 2O_2 \rightarrow NO_3^- \; H^+ + H_2O + \text{microorganisms}$$

$$\text{Organic matter} + NO_3^- \rightarrow N_2 + \text{microorganisms}$$

Ammonia is produced from the decomposition of organic matter. If the sludge age is high enough and other environmental conditions are suitable, nitrifying bacteria establish and convert the ammonia to nitrates. Oxygen requirements for the process rise because of nitrification.

The only input to an activated sludge process is the energy used to run the aerators. Since this is the largest single electrical input to any unit on the wastewater treatment and recycling plant it was decided to perform an in depth investigation of the method of aeration and look at other possible aeration methods.

The aerators in an activated sludge treatment process have four functions:

1. Ensure an adequate and continuous supply of dissolved oxygen for the bacteria
2. Keep the mixed liquor in suspension

3. Mix the incoming wastewater and the mixed liquor

4. Remove from the solution excess carbon dioxide resulting from the oxidation of organic matter

Two types of aeration systems can be used, mechanical aerators, in which a surface aerator is used to transfer gas into the mixture, or a diffused air system, where gas is injected directly into the system.

Mechanical aeration

The oxygenation is achieved by the mechanical action of the aerators, which entrain bubbles of air into the liquid. The shearing action of the aerator continuously creates new gas – liquid interfaces for mass transfer. Because gas transfer causes turbulence and mixing, aeration devices play a significant role in mixing and are therefore designed to supply the required degree of mixing as well as providing enough oxygen.

Diffused aeration

This system utilises air, which is pumped directly to the mixed liquor, under pressure into the aeration tank, where it is released as a stream of bubbles. Currents set up by the rising bubbles achieve circulation and mixing, while oxygen transfer takes place between the air bubble and the surrounding liquid.

The diffusers are categorized as either fine or coarse bubble systems depending on the bubble size. Fine bubbles are classified as those with a diameter less than 1.5 mm and coarse, those with a diameter greater than 3 mm. The finer the bubbles the larger the air – liquid interfacial area per unit volume of air resulting in more efficient transfer of oxygen. The oxygen transfer is relatively low for coarse bubbles and these are therefore used in tanks deeper than 4 m.

Table 2-1 shows the decrease in transfer efficiency with increasing bubble size. (Gray, 1990)

Table 2-1: The volume of air required and the oxygen transfer efficiency both vary for different bubble sizes (Gray, 1990).

Bubble size (mm)	**Air vol req (m^3/kg) BOD removed**	**Oxygen transfer efficiency (%)**
Fine (1.5)	36-72	11
Medium (1.5-3)	60-120	6.5
Coarse (3)	70-140	5.5

The energy efficiency of each type of oxygenation method is measured in terms of the mass oxygen transferred for the use of one kilowatt hour electricity. Typical oxygen transfer efficiencies are shown in Table 2-2;

Table 2-2: Oxygen transfer efficiencies of different aeration methods (Gray, 1990)

Aeration method	Energy efficiency ($kg\ O_2/kWh$)
Coarse bubble diffusers	0.8-1.2
Fine bubble diffusers	2.0-2.5
Vertical shaft aerators	1.5-2.3

From Table 2-2 it can be seen that fine bubble systems are the most energy efficient, however, there are many problems associated with this method which make it a less attractive option. The small pore size of the gas diffuser inevitably results in blockages both from the inside, due to dust from the air supply, or sloughed material from the pipe work or air ducts or from the outside due to deposition of solids, development of chemical scale, and bacterial slimes.

The system currently in place at the works has two treatment lanes with four aerators each. The first aeration tanks in each lane also have submerged oxygen diffuser as well as surface aerators. This is for periods of high flow through the activated sludge unit.

Screw pumps are used to return the activated sludge because of the reduced turbulence as compared to centrifugal pumps which prevents the breakup of the biological flocs.

2.4.2.2. Clarifiers

Clarification is the removal of particulate matter, chemical floc and precipitates from suspension through gravity settling. A circular type clarifier is used in the secondary treatment plant. The influent enters through a vertical riser pipe in the centre with outlet ports discharging behind a circular inlet well. This baffle dissipates the horizontal velocity by directing the flow downward. Radial flow from the centre is collected into the effluent channel attached to the outside wall by overflowing V-notch weir along the edge of the channel.

The purpose of gravity settling is to collect biological growth, or humus. These sloughed solids are generally well oxidized particles that settle readily. Therefore, a collector arm that slowly scrapes the accumulated solids toward a hopper for continuous or periodic discharge gives satisfactory performance. Gravity separation of biological growths suspended in the mixed liquor of aeration systems is more difficult. Greater viability of activated sludge results in lighter, more buoyant flocs with reduced settling velocities. In part, this is the result of microbial production of gas bubbles that buoy up the tiny biological clusters.

2.5. Durban Water Recycling Plant

The Durban Water Recycling (DWR) plant was commissioned in May 2001 and is operated by Veolia Water. The plant is designed to treat 47,5 Ml/d of domestic and industrial wastewater.

The Durban Water Recycling plant receives treated effluent from the Southern Wastewater Treatment Works and treats it to a standard acceptable for industrial use. The recycled industrial water is purchased by industry within the eThekwini Municipality, with an adjacent pulp and paper mill being the main customer. The other main customer is an adjacent oil refinery. Major benefits include a reduction in the overall industrial consumption of potable water and a decrease in the sewage load released into the environment. Industry also gains as the industrial water is less expensive and allows a significant reduction in operating costs (Gisclon et al., 2002).

The recycling plant will be referred to as the tertiary treatment plant. Figure 2-7 shows the five unit operations into which the tertiary treatment plant was divided.

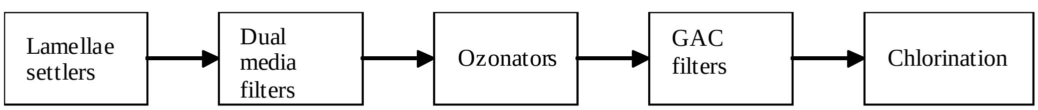

Figure 2-7 Block diagram of the tertiary treatment section of the Southern Wastewater Treatment Works.

The overflow from the clarifiers in the secondary treatment plant enters the tertiary treatment plant. This water is then pumped into a mixing chamber where chemicals are added and then sent to the lamellae settlers. For the purposes of this project the settlers and the mixing chamber were modelled as one unit. From the settlers the water flows by gravity to a dual media (sand/anthracite) filter, then to an ozonation chamber and then to a bank of granular activated carbon (GAC) filters. The carbon filters are operated in biological mode. Before being sold to the customers the water is chlorinated and pumped to a storage tank.

The main customers for the recycled water are an adjacent paper mill and petroleum refinery. Almost 40 water quality parameters are continuously monitored by automatic on-line sampling and analyzing equipment. The recycled water produced by the plant meets or exceeds the South African Class 1 (SABS 241: 1999) potable water standards in 96% of the parameters measured.

The Class 1 potable water standard gives the quality of water that is known to be acceptable for whole lifetime human consumption.

At full operational capacity the recycling plant can meet 7% of the city's current potable water demand and will reduce the city's treated wastewater output by 10% since the recycled water is not recovered after use.

2.5.1. Lamellae settlers

The first step in the treatment process is lamellae settling. The technology employed is the Vivendi Water Systems patented Multiflo process. The lamellae plates are inclined at 60^0 to the horizontal and assist the settling process. The upflow velocity through the settlers is 20 m/h.

Lime is dosed to the rapid mixers at the inlet of the lamellae settlers to precipitate primarily phosphate as calcium phosphate and remove heavy metals simultaneously. The lime injection precipitates first the calcium hardness, and then the magnesium hardness. The chemical components $CaCO_3$ and $MgCO_3$ precipitate in the water in a solid form of relative high density. Suspended solids and some other particles are captured with the precipitates. Silica (SiO_2) is adsorbed on $MgCO_3$ and settles in the same way.

The settling zone is equipped with modules, which are made up of inclined slats with a prismatic profile. Thus two back-to-back slats form a module composed of sections with a hexagonal cross-section. The water circulates upwards between the slats in the opposite direction to the flocs, which deposit on the plates and slide downward under the effect of gravity.

The falling distance for the flocs is limited to the maximum extent possible, associated with inclining of the plates to make them settle in a zone where they will be concentrated. To prevent shearing of the flocs when water currents and the flocs interact, the settler plates are sufficiently close to enhance settling, whilst preventing the phenomena of floc shearing when they slide to the bottom of the settler.

Internal recirculation of the settled sludge to the rapid mixers improves the reaction kinetics, flocculation and subsequent settling of the flocs. One recirculation pump per lamella settler continuously draws settled sludge from the bottom of the settler structure and pumps at a constant rate (5% of the max flowrate) to the rapid mixer at the inlet of the settlers (IMIESA 1999).

2.5.2. Dual media filtration

The dual media filtration is the last solids barriers in the process. The settled water flows by gravity after neutralisation from the lamellae settlers to the dual-media filter plant. This is a deep bed filter with an anthracite layer covered by a sand layer. The filters have a bed depth of 3 m, the top metre being anthracite and the rest silica sand. The dual media filters and the GAC filters both share the same set of backwash pumps and air blowers for cleaning purposes. Filtration velocities of 14 m/h are achieved and the current filter cycle is 36 h.

The addition of a coagulant and polymer enhances the performance of the filter.

2.5.3. Ozone production and ozone contact tank

Ozone gas is dosed for effective disinfection, colour removal and breakdown of complex organic matter. Ozone reacts rapidly to inactivate microorganisms, oxidising iron, manganese, sulphide and nitrite and reacts slower in oxidising organic substances, such as pesticides, volatile organic chemicals and other organic compounds. The rapid oxidation reactions occur in relatively short contact time compared to oxidation by chlorination. As ozone is a highly toxic substance, no ozone is stored on site, and the instant demand is supplied by two ozone generators from pure oxygen.

The ozone is introduced into the water phase by fine bubble diffusers mounted on the bottom of the ozone contact tanks. The tank is arranged in two lanes in order to allow for maintenance and repairs without interruption of the process. The ozone contacting time is 15 min. Two Trailigaz ozone generators with a maximum combined output of 12 kg/h are employed.

Residual ozone in the vents is eliminated in two thermal ozone destructors to harmless levels. The thermal destruct unit (TDU) is made up of a heating element, which is maintained at 350 ^{o}C, over which the gas is passed. The TDU is largely responsible for the high electricity consumption of the ozonation unit.

Since ozone does not produce a disinfecting residual, chlorine must be added to the treated water to establish a protective residual and control bacterial growths in the distribution piping network.

2.5.4. Granular Activated Carbon Contactors

Water flows from the ozone contact tank to the granular activated carbon (GAC) contactors in a concrete channel that distributes the flow on four contactor cells. The contactor is similar to the dual media filter except it has a single granular activated carbon bed. Its purpose is to provide contact of bacteria fixed on the activated granular carbon with the water. The GAC is employed as a polishing step and for the removal of ozone degraded organics. The bed depth is 3 m and the contacting time is 10 min. The carbon used is Picobio and a bed life of 8 to 10 years is expected.

2.5.5. Chlorine contact tank

The chlorine contact tank is used for final disinfection of the reclaimed water. It is necessary to maintain a residual chlorine content in the treated water to control bacterial contamination. The tank is covered with a light roof to ensure that no contaminants can enter the reclaimed water in the last stage of treatment.

The chlorine contact tank also functions as a pump sump for the fixed speed reclaimed water pumps.

2.5.6. Chemicals used

Hydrated lime is used for pH correction and phosphorous removal. The lime is dosed to the water in the form of a slurry that is automatically prepared.

Polyaluminium chloride is used as a coagulant for direct filtration on the dual media filters to enhance filter performance.

Ferric sulphate is used for phosphorous removal and can be dosed into the aeration tanks if required for decarbonation in the lamellae settlers.

Carbon dioxide is used for pH neutralisation after lime addition.

Oxygen is used for ozone production and can also be dosed to the aeration tanks and increase the aeration capacity of the secondary treatment plant.

Chlorine is dosed for disinfection purposes to the reclaimed water prior to pumping to the high-level storage tank.

A generic *polymer* called Zetafloc is used to aid the flocculation process.

2.6. Disposal to sea

The eThekwini Municipality has been discharging sewage and selected industrial wastes through its two deep sea submarine outfalls since about 1970. The outfall is a gravity fed pipe, 4.2 km long and 1.37 metres in diameter which discharges at a depth of 60 m. This ensures that by the time the effluent reaches the surface, it has a dilution factor of at least 250 (Carter, 2003).

The outfall and its effect on the marine environment have been monitored, since its inception, by the Council for Scientific and Industrial Research (CSIR) and the eThekwini Municipality. To date the results from the monitoring programme have generally shown compliance with the permit conditions under which they operate and, within their limitation, demonstrated minimal impact on the marine environment (Carter, 2003)

2.7. Discussion

The system to be studied has been described in this chapter. It is important to understand the workings of the system in order to analyse the environmental impacts. The chapter traces the abstraction of water at Inanda Dam and follows this water network up until the final disposal of sludges in the Southern Wastewater Treatment Works deep sea outfall. Chapter 3 follows and shows how the LCA methodology was used to quantify the environmental burdens of the system.

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Chapter 3 : Environmental Life Cycle Assessment

Environmental Life Cycle Assessment (LCA) gained popularity in the 1990s, however, it had been used as early as 1960 when several "fuel cycle" studies were conducted in the United States by the Department of Energy. The oil shortages in the early 1970s drove the British and U.S governments to conduct detailed energy analysis studies using many techniques which have been subsequently incorporated into the LCA methodology.

The 1980s saw renewed interest in LCA by the Green Movement in Europe bringing to public attention issues related to recycling. LCA interest has been driven by large industrial companies interested in showing environmental superiority over a competing product. One of the first life cycle type studies carried out in the United Kingdom was an energy study on returnable and non-returnable beer bottles. (Boustead, 1996) While product comparison is still the goal of many groups, especially in ecolabeling programs, identifying opportunities to alter a product, or process, to improve its environmental profile is now often the motivation behind conducting an LCA. The last few years have seen a significant increase in research activity in this area by both government and private industry. (Rebitzer et al, 2004)

Life cycle assessment (LCA) is a systematic way to evaluate the environmental impacts of products or processes by following a scientific methodology in which the impacts are quantified. The ISO 14040 series for life cycle analysis (International Organisation for Standardisation, 1997), lists the applications as including: identification of improvement possibilities, decision making, choice of environmental performance indicators and market claims. LCA has two main objectives. The first is to quantify and evaluate the environmental performance of a product or process and so help decision makers choose among options. Another objective of LCA is to provide a basis for assessing potential improvements in the environmental performance of the system. (Azapagic, 1999) Once these areas and the contributors to the high burdens are identified, improvement options can be investigated and implemented.

This LCA was carried out using the standard ISO 14040 methodology. This comprises four stages;

- goal definition and scoping
- life cycle inventory
- impact assessment
- interpretation improvement assessment

Figure 3-1 shows how all the phases of an LCA study interact with one another and how LCA is an iterative process.

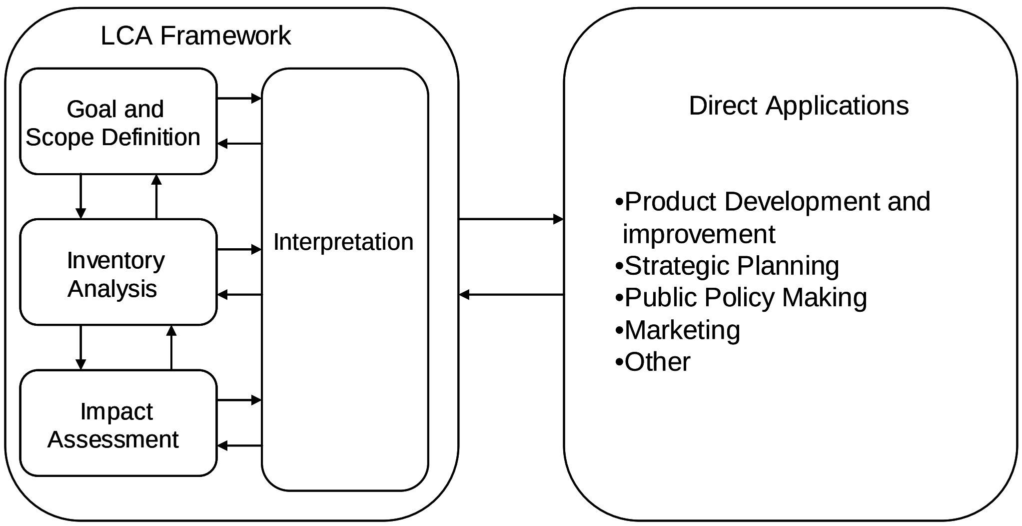

Figure 3-1: Phases and applications of an LCA (based on ISO 14040, 1997)

This chapter presents a brief explanation of each stage of the LCA methodology as well as the results of each stage. Hypothesis and assumptions are stated before the results are presented. A discussion of the results concludes each section. Section 3-1 presents the goal and scope of the study. The system boundaries are identified and the chosen functional unit explained. The inventory analysis stage of the LCA is discussed in Section 3-2. Section 3-3 deals with the impact assessment stage. The impact models and methods used to calculate the environmental loads are discussed here. The chapter concludes with the final stage of an LCA the interpretation phase in Section 3-4. The chapter ends with a discussion in which the validity of the assumptions are checked and key findings that the LCA has highlighted are presented.

It is important for the reader to be aware of the order in which the sub-sections were studied. This is necessary since as the study progressed a better understanding of the LCA methodology was gained which allowed for a better focused study.

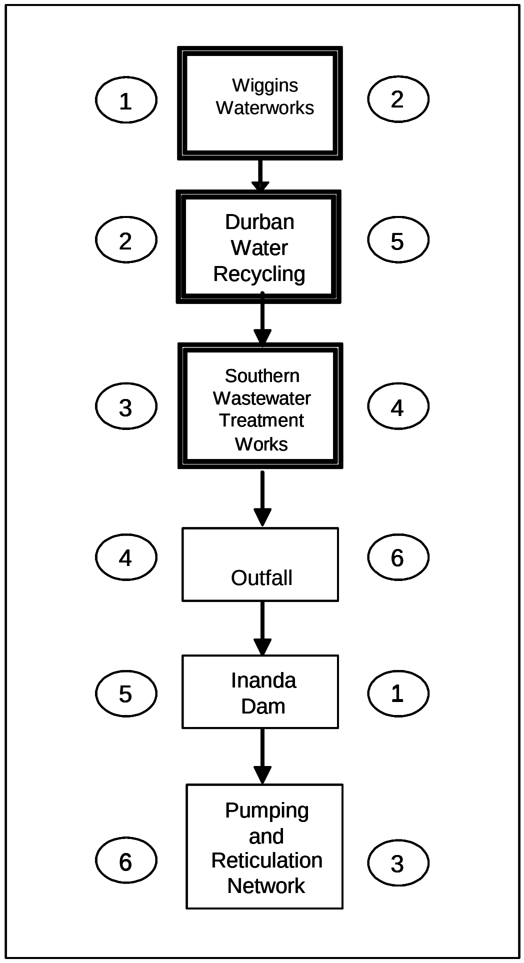

Figure 3-2: Diagram showing the order in which the LCA was carried out. The numbers on the left indicate the order in which the units were studied and the numbers on the right their logical order. The boxes encased by a double line indicate that a detailed LCA was carried out on the sub-system while a single line indicates a streamlined LCA.

The first sub-section studied was Wiggins Waterworks initially by Friedrich, 2001. As the construction of the Durban Water Recycling plant was nearing completion at this time this was the next unit studied since inventory data were readily available. The primary and secondary treatment plants were next followed by the deep sea outfall and finally Inanda dam. As the study progressed to the later two sub-sections it was hypothesised that the LCA could be streamlined with little impact on the accuracy of the results and a vast time saving. The streamlining method of the LCA is presented when each unit is discussed as well as the assumptions that were necessary. This streamlining method involves initially calculating a rough overview of the sub-systems impacts allowing one to decide whether the impacts are significant and a whether detailed or comprehensive LCA is required. The SETAC data working group has used this approach and has shown that for several applications, the time and cost of a detailed LCA study are judged to not correspond to the possible benefit of the results (SETAC Data WG, 1999). This approach is generally referred to as a hybrid LCA (Suh and Huppes, 2002).

When presenting the results it was felt that it would be better to follow the logical chain of the water supply network. Thus the results are presented starting at Inanda dam and ending at the deep sea outfall.

3.1. Goal and scope

This includes definition of system boundaries, details, accuracy and data quality, functional units and impact models to be used for the analysis. The goal of this study is to assess the environmental impacts associated with production of water and to highlight the processes contributing the most to these impacts.

3.1.1. Theory and methodology

The goal definition and scoping stage of LCA defines the purpose of the study, the expected product of the study, the boundary conditions and the assumptions. (SETAC, 1992) Typically LCA studies are performed in response to specific questions. The nature of the questions determines the goals and scope of the study.

Once the general goals and purpose of the LCA study are understood, the boundaries of the study must be determined. It is common practice to define the life cycle of the product, process or activity being studied as a system (Boustead, 1992). In this study the system is defined as a water and sewage network within the eThekwini Municipality. The boundaries for the LCA encompass the acquisition of raw materials, manufacture of intermediate materials, manufacture of the product being studied, use of the final product and final disposition. Recycling or reuse of the product is part of the methodology. When conducting an LCA, the design/development is usually excluded, since it is often assumed not to contribute significantly (Rebitzer et al., 2004). After all steps that fall within the system boundaries are identified, the LCA practitioner may choose to simplify the LCA by excluding some steps from the study. Hypotheses have been outlined and where steps have been excluded these are explained.

Heinz and Baisnee (1992) and Weidema (1993) suggested that two distinct categories of LCA goals exist. These are;

- to describe a product system and its environmental exchanges or
- to describe how the environmental exchanges of the system can be expected to change as a result of actions taken in the system.

This study shares both goals. In this chapter the first goal is addressed that is to describe the environmental profile of each unit. A stand alone LCA was performed on each unit in the studied system. All four steps of the ISO methodology were carried out including an improvement analysis.

The second goal is dealt with in Chapter 6 where different scenarios are considered. Chapter 6 links the individual LCAs performed in this chapter by using a different functional unit. This allows one to understand the environmental burden of the system as a whole and to then understand the effect changes will have to the system's environmental profile.

Part of the formal goal definition process is a requirement that the reasons for the study and the intended audience be identified. Currently in South Africa there is a drive to expand the provision of water and sanitation services. However in order to this in a sustainable manner one needs a clear understanding of the associated environmental burdens. There are many options that can be considered for these expansions. This LCA study in this chapter aims to provide detailed information on the environmental burdens of the processes currently in use in the eThekwini Municipality. This will aid planners and water professionals (the intended audience) when considering the different expansion options. Chapter 6 considers expansion scenarios and examines options that are not currently in use in the eThekwini Municipality.

Time and spatial boundaries must also be chosen for the study. The goal of the LCA is to model, as closely as possible the life cycle of the product, process or activity being studied. Spatial boundaries need to be evaluated in this context. Time boundaries are also important because industrial practices, legislative requirements and consumer habits vary over time.

3.1.1.1. Consequential vs Attributional LCA

It is important to decide, during the goal definition phase of the LCA, whether to conduct a consequential or attributional LCA. During a workshop held in 2003, specifically on life cycle inventory for electricity generation the term *attributional life cycle assessment* was defined as an attempt to answer *how are things (i.e. pollutants, resources and exchanges among processes)* flowing within the chosen temporal window while *consequential life cycle assessment* attempts to answer *how will flows beyond the immediate systems change in response to decisions?* For example, an attributional LCA would examine the consequences of using green power compared to conventional sources. A consequential LCA would consider the consequences of this choice in that only a certain amount of green power may be available to customers, causing some customers to buy conventional energy once the supply of greener sources was gone (Curran, Mann & Norris, 2005).

The is much debate amongst LCA practitioners on which type of LCA is better. Attributional LCAs are generally retrospective assessments of the accountancy type and are typically applied for hot-spot identification, product declarations and for generic consumer information. Consequential LCAs study the environmental consequences of possible (future) changes to the system being studied.

One of the stated aims of this thesis is to determine the net effect of using recycled water. Therefore it is necessary for the consequential method to be used. This means that processes or data used should represent the consequential technologies (i.e. as a consequence of recycling). For example the consequential production technology should be included i.e. the electricity production technology that will respond to a small increase or decrease in demand. In South Africa this is coal based electricity generation and this was therefore used when compiling the life cycle inventory.

3.1.1.2. Functional unit

The functional unit is defined as a quantified description of the performance of the product system for use as a reference unit. Special attention has to be given to choosing the functional unit because it provides a reference to which the input and the output data in the inventory phase will be related. The functional unit of this study is defined as 1 kL of water at the qualities stipulated by the Umgeni Water guidelines for potable water and the eThekwini Municipality for wastewater treatment. Each sub-system produces a different product (i.e. different quality of water) therefore it is not possible to use a constant /consistent functional unit throughout the study of each unit. It was decided that the functional unit would be one kilolitre of the water produced from each sub-system at the stipulated quality. For example when studying the wastewater treatment plant the functional unit is one kilolitre of treated wastewater produced and for the recycling plant the functional unit is one kilolitre of recycled water produced. Rihon (2002), in a similar study which investigated the environmental impacts of an 'anthropic water cycle' from the pumping station to the wastewater treatment plant, also chose to use a similar functional unit. Friedrich (2001) used a similar functional unit when considering water treatment processes. When considering the complete system it was necessary to use a different functional unit as one cannot simply consider the volume weighted sum of the different impact categories.

Having defined the functional unit, it is necessary to quantify the amount of product which is necessary to fulfil the function. The result of this quantification is the reference flow.

3.1.2. Assumptions

A study on the influence of system boundaries (Lundin, 2000) highlighted the fact that very different choices can be made for system boundaries in models of water and wastewater systems. These choices inevitably affect the results. Most LCAs include only the operation of the studied technical systems and overlook the environmental load of the construction phase. Consequently questions related to the scale and longevity of the systems are also overlooked.

For the purpose of this study, the construction, operation and decommissioning phase of each sub-system was studied. Equipment was assumed to last the entire predicted design lifetime. For example Inanda Dam is designed to operate for a period of 70 years. However this is highly dependent on the silting rate of the dam but for calculation purposes 70 years was the figure used.

Each sub-system produces a different product therefore it is not possible to use a constant /consistent functional unit throughout the study. It was decided that the functional unit would be one kilolitre of the water produced from each sub-system. For example when studying the wastewater treatment plant the functional unit is one kilolitre of treated wastewater and for the recycling plant the functional unit is one kilolitre of recycled water. Rihon (2002), in a similar study which investigated the environmental impacts of an 'anthropic water cycle' from the pumping station to the wastewater treatment plant, also chose to use a similar functional unit. In considering the complete system, the volume weighted sum of the different impact categories was calculated.

Neither production nor demand is always fully elastic, which means that the demand for one unit of product in the life cycle investigated affects not only the production of this product but also the consumption of the product in other systems (Ekvall, 2002). It was assumed that for the purposes of this model the system would be operating under what would be considered normal conditions.

3.2. Life cycle inventory analysis

The object of the inventory analysis is to collect environmentally relevant information from the processes identified during the scope definition.

3.2.1. Theory and Methodology

At the start of the life cycle inventory analysis (LCI) it is important to identify the relationship between the process and the environment and to find the correct unit to describe these exchanges. For materials, the correct unit is typically the weight of the material and the exchanges are expressed *per kilogram*. This is the same for raw material extraction and material production. For electricity generation the typical unit is *1 kWh* of electricity generated. When describing transportation of materials the typical units used are *km*, *loaded weight* and *speed* combined with *type of transport* (Wenzel, 1997).

The data collection is the most time consuming part of the LCA. During this step qualitative and quantitative information concerning the different processes in the product chain is gathered. In the early days of LCA use, attempts were made to convert economic data into their physical equivalent since economic data are generally well recorded and monitored by companies. However two serious shortcomings prevent this from being viable. First the economic groupings are generally too broad to allow specific processes to be isolated and secondly, economic value changes differently in different economic sectors so that the idea of defining an energy intensity (i.e. MJ/$) as a means of converting monetary value to physical quantity is almost impossible. (Boustead, 1996) As outlined in Table 3-1 there are usually four stages to an LCI;

Table 3-1 General procedure for data collection during the life cycle inventory stage (Wenzel et al, 1997)

1. Literature information retrieval: Data are extrapolated from similar processes described in available literature. Knowledge centre are contacted for relevant available information: papers, books, reports, LCA reports, electronic databases and data networks.

2. Questionnaire: Data are sought from contractors etc. Personal contacts are established at the relevant companies. Questionnaires are sent out and the contact is followed up. A visit will often be necessary to assist the contractor and avoid misunderstandings.

3. Calculations: Processes and data are examined in order to reveal to what extent the emissions can be calculated as described in the next paragraph. Calculations are carried out.

4. Measurements: Measurements are carried out for processes where this is judged to be desirable or necessary, and/or because sufficient data cannot be obtained by other means.

The value of the LCA depends largely on the quality of data in inventories. An important and often neglected fact is that all incoming mass should be found somewhere on the output side of the balance (Ayres, 1994). Often the software used to perform the LCA maintains a consistency check on the mass inputs and outputs as was the case in this study.

3.2.2. Assumptions

As the data collection is a time and cost intensive step, the life cycle can be divided into two parts – *background* and *foreground*, (Seungdo et al., 2001; Azapagic, 1999), to facilitate the data collection. For a *background* process in a sub-system, secondary data are used instead of collecting site specific data. The *background* system is that which supplies materials and energy to the *foreground* system, usually via a homogenous market so that individual plants and operations cannot be identified. For example, commercial databases were used for raw material extraction, material production and energy production. The *foreground* system is defined as the set of processes directly affected by the study. Processes of the primary suppliers and processes within the plant are defined as *foreground* and site specific data are collected.

The analysis was further simplified by considering only primary inputs of energy and materials, as previous studies (Hunt, 1991) have demonstrated that secondary effects (such as construction of manufacturing plants, for chemicals used, and manufacture of vehicles, for transport) account for less than 5% of the total impact to each phase.

As the study progressed it became clear that the impact from the construction stage was small. It was decided to use an iterative process to complete the LCA for an individual sub-system. The first step was a quick run through which involved a lot of estimation to calculate the inventory lists. This step served to establish whether the construction phase would have a significant impact or not. If the impact of the construction phase proved to be less than 5% of the total impacts then this stage was discarded. Only if the contribution was greater than 5% was it included.

Whenever data was missing, the missing data were calculated assuming worst case conditions. Thus the final impacts calculated may be slightly higher than the actual impacts of each sub-system. The data quality is evaluated in Appendix 4.

3.2.3. Results

As stated in the previous chapter the study was broken up into the following systems; Inanda Dam, Wiggins Waterworks, Pumping and Reticulation Network, Southern Wastewater Works, Durban Water Recycling and the Durban South Deep Sea Outfall. These sub-systems will now be discussed separately and a combined result presented and consolidated into a description of the complete system. The individual LCIs of each sub-system and the accompanying assumptions will now be presented.

3.2.3.1. Inanda Dam

When considering the dam the following specific assumptions were made.

1. Since the dam is designed for a minimum of 70 years of operation and during these years millions of kilolitres of water are produced, the impacts of the construction phase are small. In a study on the construction of hydroelectric dams it was concluded that, '*…the emissions related to the building of the plant are considerably inferior to those coming from a reservoir (about 40 times)…*' (Carvalho, 1999) It was suspected that the impact of the construction phase of the Inanda dam would be small. Several order of magnitude calculations were carried out to determine the impact of the dam as compared to the whole system. These calculations are presented in Appendix 1. Thus based on the order of magnitude calculations it was decided to exclude the contribution from the construction phase. One must remember that the impacts being referred to are those impacts that fall within the LCA impact categories chosen. Thus the impacts such as

changes in the geomorphology of the dammed river are not considered. However in order to present a holistic picture these impacts were investigated and are presented in Appendix 1.

2. Similarly the environmental impacts resulting from the decommissioning of the dam are small (again see order of magnitude calculations in Appendix 1) and are therefore not included.
3. The energy inputs during the operation of the dam are negligible since the only energy inputs are for the monitoring and control equipment at the dam.
4. The major environmental impacts result from the emissions of the dam. This is due to the decomposition of the biomass entering the dam.
5. The emissions from the decomposition of organic matter that would have occurred if the dam was not constructed are assumed to have been small. This is due to the fact that these emissions would have resulted from the aerobic decomposition of the organic matter resulting in the generation of carbon dioxide. In the dam the majority of the decomposition takes place anaerobically, generating methane. Since the contribution to global warming from methane is so much greater than that of carbon dioxide the aerobic generation was not considered to be significant. Thus this figure was not subtracted from the total generated by the dam.

The science of measuring emissions from dams is in its infancy. There have been no studies of the emissions from dams in South Africa. Therefore in order to estimate missing data it was necessary to use measurements from Brazilian dams as these best approximate South African conditions (Rosa, 2000). The reason for choosing the Brazilian emission models was due to the fact that the volume of dam emissions is dependent on the ambient water temperature. Dams in the northern hemisphere e.g. Canada and Norway have much lower emissions than dams in higher temperature regions. The Brazilian model is the closest to the temperature range of Inanda dam. Even though the temperature of the Brazilian dams are slightly higher than that of Inanda dam the science of calculating dam emissions is so inexact that it is better to over-estimate the emissions in order to present a worst case-scenario.

Gases are produced in dams due to bacteria breaking down the organic matter in the water. Methane is produced in oxygen-poor zones common at the bottom of the dam and carbon dioxide in the aerobic zones.

The crucial input to consider to the dam is the total organic carbon (TOC) entering the dam. The TOC of water entering Inanda Dam is approximately 4.50 mg/l. This TOC decomposes and methane and carbon dioxide gas are produced. These are the harmful emissions from the dam which cause global warming. This is the only inventory aspect that was considered. A detailed description of how these emissions were calculated is presented in Appendix 1

3.2.3.2. Wiggins Waterworks

Table 3-2 shows the material and energy consumption for Wiggins Waterworks (after Friedrich, 2000). This was the first sub-system studied and the results showed that 98% of the material inputs and almost 96% of the energy inputs for the system could be traced to the operations stage. The raw data can be found in the master's thesis of Friedrich (2002). The contribution from the construction stage is small.

Table 3-2 Material and Energy Consumption for the Wiggins Waterworks for Construction, Operation and Decommissioning

Stage	Material Consumption (kg/kl)	Energy Consumption (MJ/kl)
Construction	0.00515	0.00873
Operation	0.27000	0.20670
Decommissioning	0.00002	0.00015

Table 3-3 presents the mass outputs associated with all three phases of Wiggins Waterworks. The outputs can be divided into four major categories: emissions to air, emissions to water, deposited goods and production residues in the life cycle. Emissions to air and water include, heavy metal, inorganic, organic, radioactive and particle emissions. Deposited goods include consumer waste, stockpile goods, hazardous waste and radioactive goods. Production residues in the life cycle are wastes for recovery.

Table 3-3: Mass outputs per kilolitre associated with the Construction, Operation and Decommissioning of Wiggins Waterworks.

Output	Mass (kg/kl)
Emissions to air	0.17205
Emissions to water	0.004207
Deposited goods	0.00079
Production residues	0.00095

3.2.3.3. Distribution and collection network

The water exiting Wiggins Waterworks flows almost entirely by gravity to consumers. However there is considerable energy usage involved in the collection of the wastewater streams. Preliminary calculations (Friedrich and Pillay, 2005) showed the construction phase to have a significant impact on the overall burden and thus this stage was included. The results are presented here.

Distribution

There are three types of pipe used in the distribution network; asbestos cement, steel and modified polyvinyl chloride (MPVC). The lifetime of the asbestos cement and steel pipes was taken as 60 years and the MPVC 20 years. For the studied system, the inputs per kilolitre water transport are presented in Table 3-4.

Table 3-4: Inputs per kilolitre of water transported for the different pipes in the distribution system.

Input	Quantity	Unit
Asbestos cement	22	g/kl
Steel	11	g/kl
MPVC	0.27	g/kl

For the operation of the distribution network the only input considered was the electricity used for pumping. If one takes into account that there is a 30% loss in the distribution system (eThekwini Municipality Wastewater Services Report) the energy figures are calculated as 0.468 MJ/kl of potable water delivered to customers.

Collection

There are mainly two types of pipe in the collection network; asbestos cement and vitrified clay. After discussions with the operating personnel it was decided to assume that 40% of the existing sewage pipes are asbestos cement and 60% vitrified clay. This was assumed for pipes of all diameters. The life of the asbestos cement was again taken to be 60 years and the vitrified clay 100 years.

Another input to the collection network is the concrete used for the construction of manholes. For this study it was assumed that the upper cover and base of the manhole was also constructed of concrete. The inputs to the collection network are summarised in Table 3-5.

Table 3-5: Inputs for the pipes and manholes used for the construction of the wastewater collection network (per kl wastewater collected).

Input	Quantity	Unit
Asbestos cement	0.0086	kg/kl
Vitrified clay	0.0060	kg/kl
Concrete	0.132	kg/kl

Again the only input considered for the operation phase is that of the electricity associated with the pumping. This was calculated to be 0.504 MJ/kl of wastewater moved in the system.

3.2.3.4. Southern Wastewater Treatment Works

As discussed in Chapter 2, the Southern Wastewater Treatment Works comprises the primary and secondary treatment plants. As this was the second unit studied a more detailed investigation was undertaken in order to create a better picture so a decision could be made on whether to include or discard the construction and decommissioning stages in the other sub systems. Thus in this section of the study a further level of detail was added by breaking up each sub-system into individual process units.

Again the LCI was broken into three basic phases; construction, operations and decommissioning.

Primary Treatment Inputs - Construction phase

The mass inputs to the construction phase come from the concrete used for the civil works, metals used for the pumps and steel used for the construction of the screws used in the screw pumps. The screw and drive motor were taken as being separate pieces of equipment. Therefore the motor was modelled, as were the other pumps as having a lifespan of 5 years (Friedrich, 2001) and the screw was taken as lasting the life of the plant i.e. 30 years. Table 3-6 shows these inputs. This takes into account the spare parts used in maintaining the pump and is a worst case scenario.

Table 3-6: Mass inputs to the construction phase of the primary treatment

	Inlet works (kg)	Screen/ degrit (kg)	Screw pumps (kg)	Elevated channel (kg)	Primary settling (kg)
Steel sheet	0	0	1192.5	0	0
Concrete	2.15E05	5.50E05	1.87E05	6.55E05	1.47E06
Pumps	0	0	6744	0	324

The concrete used is 30 MPa and the inputs associated with the production of 1 kg of concrete are presented in Table 3-7 .The reinforcing steel used in the concrete structure is included as part of the mass of the concrete. Both the production of concrete and the pumps were designated as foreground processes and therefore a detailed analysis of the inputs and outputs was undertaken.

Table 3-7: Inputs associated with the production of 1kg of concrete.

Inputs	Mass (kg/kg concrete)
Sand	0.24
Stone	0.49
Steel	0.05
Cement	0.14
Water	0.07

The inputs for the production of a pump on a per kg basis are presented in Table 3-8 below. One must remember that when these metals are included in the inventory all the processing steps to refine the metals are also included.

Table 3-8: Inputs associated with the production of a pump on a per kg basis.

Inputs for a pump	Mass (kg/kg pump)
Aluminium	0.25
Steel	0.64
Copper	0.11

Primary treatment inputs- Operations phase

The only input for the operations stage is electricity. The electrical input to this process is 0.37 MJ/kl for the raw screw pumps and 0.007 MJ/kl for the primary settling tanks.

Primary treatment inputs - Decommissioning

It was assumed that the plant would be demolished and transported to a landfill site. Metal from the pumps and steel reinforcing that can be recycled where taken as being transported to a recycling facility. It was not within the scope of this study to include the environmental burdens associated with recycling the metals, as most of the metal recycling is not done in South Africa.

Outputs

Appendix 5 contains a full breakdown of the inputs and outputs. The main outputs are presented in the following section.

Primary treatment outputs - Construction

The mass outputs per kilolitre of wastewater treated can be seen in Table 3-9 below.

Table 3-9: Mass outputs associated with the construction of the primary treatment plant.

Outputs	**Mass (kg/kl)**
Emissions to air	1.27E-03
Emissions to water	3.081E-05
Deposited goods	9.546E-07
Production residues	1.20E-04

Primary treatment outputs - Operations

The only input for the operations stage is the electricity used in the screw pumps and the motors used in the primary settlers. The inputs and outputs associated with the production of electricity will be discussed in greater detail in Chapter 5, associated with the production of electricity.

Primary treatment outputs - Decommissioning

The inputs for the decommissioning stage come from the diesel used for transporting the rubble to a landfill site. It was taken that the nearest landfill site would be 50 kilometres away. It was also assumed that 30 percent of the steel from the concrete would be recycled and all the metals from the pumps would be taken to a recycling facility. Therefore for every 1 kilogram of concrete 0.016kg of steel would be recovered.

Again the LCI was broken into three phases; construction, operations and decommissioning for the analysis of the secondary treatment plant

Secondary treatment inputs – Construction

There are two main inputs for the construction stage, concrete and steel. It is important to know the inputs associated with each and these will be presented here. It was decided to include the pumps in this stage. It was taken that the life of a pump would be five years, this takes into account the spare parts used in maintaining the pump. It is a worst case scenario.

The major inputs for the construction of the activated sludge are concrete, pumps and steel used in the construction of the impellers for the screw pumps. Thus the inputs for the construction of the activated sludge unit are shown in Table 3-10;

Table 3-10: Mass inputs associated with the construction of the secondary plant.

Inputs	Activated sludge (kg)	Clarifiers (kg)
Steel sheet	596.25	0
Concrete	5.07e06	2.98e06
Pumps	568	108

Secondary treatment inputs – Operations

The only input for the operations stage is electricity. The electrical input to this process is 1.00 MJ/kl for the activated sludge process and 0.015 MJ/kl for the clarifiers.

Secondary treatment inputs – Decommissioning

It was taken that the plant would be demolished and transported to a landfill site. Metal from the pumps and steel reinforcing that can be recycled were taken as being transported to a recycling facility.

Secondary treatment outputs - Construction

Appendix 5 contains a full breakdown of the inputs and outputs to the activated sludge and clarification units. The main outputs are presented in Table 3-11.

Table 3-11: Mass outputs associated with the construction of the secondary treatment plant.

Outputs	Mass (kg/kl)
Emissions to air	3.20E-04
Emissions to water	7.94E-05
Deposited goods	2.50E-06
Production residues	3.10E-04

Secondary treatment outputs - Operations

The only input for the operations stage is the electricity used in the air blowers and screw pumps for the activated sludge unit. This amounts to 1.00 MJ/kl of water for the activated sludge and 0.015 MJ/kl for the clarifiers. The inputs and outputs associated with the production of electricity will be discussed in greater detail in the next chapter.

It was assumed that the direct emissions from the process would be small. This was based on the IPCC guidelines for calculating the emissions from wastewater treatment (IPCC, 1996). This is based on the fact than since the biological degradation is aerobic, there is very little methane production and the carbon dioxide produced has a small contribution in comparison to that from the electricity consumption.

Secondary treatment outputs - Decommissioning

The inputs for the decommissioning stage come from the diesel used for transporting the rubble to a landfill site.

3.2.3.5. Durban Water Recycling Plant

The tertiary treatment plant was broken up into the five unit operations involved.

The LCI was further divided into three phases; construction, operations and decommissioning

Tertiary treatment inputs - Construction phase

The construction of the plant uses a very compact design, with a number of the walls being shared by two units. For example the lamellae settlers are next to the dual media filters so the wall in between these units is shared. This has led to lower mass inputs for the construction stage and thus a lower environmental burden. Table 3-12 shows the mass inputs associated with the construction stage.

Table 3-12: Mass inputs to the construction phase of the tertiary treatment plant.

Inputs					
	Settlers (kg)	**DM filters (kg)**	**Ozonation (kg)**	**GAC filters (kg)**	**Chlorination (kg)**
Concrete	2.49E06	1.30E06	2.38E06	8.26E05	2.49E06
Pumps	780	320	0	0	0

Tertiary treatment inputs - Operations phase

The inputs to the operations phase include the chemicals inputs as well as the electrical input. Table 3-13 shows the chemicals inputs used during the treatment process. Zetafloc is the proprietary flocculent used as described in chapter 2.

Table 3-13: Mass inputs to the operations phase of the tertiary treatment plant per kilolitre of water treated

Inputs	Mass (kg/kl)
Quicklime	0.0305
Zetafloc	0.0017
CO_2	0.0200
$AlCl(OH)_2$	0.0051
Cl_2	0.0080
$FeSO_4$	0.0610
Total	0.1263

Electricity is the other input to the operations phase, the electrical input being 0.18 MJ/kl water treated. The electricity is used mainly in the ozonation unit with this unit using 0.15 MJ/kl.

Tertiary treatment inputs - Decommissioning

As with the primary and secondary treatment plants it was taken that this plant would be demolished and taken to a landfill site.

Outputs

Again the outputs were divided into four major categories: emissions to air, emissions to water, deposited goods and production residues in the life cycle.

Tertiary treatment outputs – Construction

Table 3-14 shows the outputs associated with the construction stage of the tertiary treatment plant.

Table 3-14: Mass outputs associated with the construction of the tertiary treatment plant.

Outputs	**Mass (kg/kl)**
Emissions to air	6.30E-03
Emissions to water	1.50E-04
Deposited goods	4.91E-06
Production residues	6.00E-04

Tertiary treatment outputs - Operations

Since electricity is not the only input associated with the operations phase it is useful to consider the outputs associated with this stage. Table 3-15 shows the outputs associated with the tertiary treatment plant.

Table 3-15: Mass outputs associated with the operations of the tertiary treatment plant.

Outputs	**Mass (kg/kl)**
Emissions to air	8.80E-02
Emissions to water	1.30E-03
Deposited goods	1.10E-03
Production residues	1.78E-05

3.2.3.6. Durban Southern Deep Sea Outfall

The Durban Southern deep sea outfall carries 150 000 m^3/d of domestic and industrial sewage into the sea. Table 3-16 highlights some of the important physical characteristics of the pipeline. The rated 150 000 m^3/d capacity is the maximum unassisted (i.e. by gravity) flow through the pipeline. In time of extraordinary high flow, 2 pumps assist the effluent flow through the pipeline. However since this study considers the normal operating conditions it was decided that the pumping of effluent was not within the goal and scope. This is a valid assumption as during the first year of the recycling plant's operation the pumps were not used at all.

Table 3-16: Effluent pumped through the Southern Deep Sea Outfall

Southern Outfall	Unit	
Present load	m^3/day	150 000
Diameter	M	1.37m
Length	M	4.2km
Composition of effluent		Domestic and industrial effluent
Average effluent quality		
COD	mg/l	2400
OA	mg/l	420
pH		6.5
Suspended Solids	mg/l	600
TDS	mg/l	2000

3.2.4. Discussion

Table 3-17 presents an overview of the inputs and outputs of the water distribution network studied. Appendix 5 contains a comprehensive breakdown of these inputs and outputs.

Table 3-17 Summary of inputs and outputs to the entire system

Construction	Operation	Decommissioning
Inputs		
Material Consumption	Treatment chemicals	Topsoil, bulkfill
Steel, iron, cement, water, aggregate, PVC, copper, aluminium		
Energy Consumption		
Outputs		
Air Emissions		
CO_2, SO_2, NOx, CO, hydrocarbons, particulates, Ash, organochlorines	CO_2, SO_2, NOx, CO, hydrocarbons, particulates,Ash, organochlorines	CO_2, SO_2, NOx, CO, hydrocarbons, particulates, ash, organochlorines
Water Emissions		
BOD, COD, SS, mercury, lead, sulphides, Phenols, organochlorides	BOD, COD, SS, mercury, lead, sulphides, Phenols, organochlorides	Negligible

Construction	Operation	Decommissioning
Solid wastes Mine waste, slag, dust, unspecified hydrocarbons, excavation wastes, wood	Sludge solids, sludge metal contents, screenings	Steel, concrete, slag, copper, aluminium, PVC

3.3. Impact Assessment

The aim of the impact assessment is to evaluate the significance of the potential impacts resulting from the inputs and outputs summarised in the inventory list. This is a process which according to the ISO methodology has 3 mandatory steps as well as a number of optional ones. The mandatory steps are; (i) selection of impact categories, category indicators and characterization models, (ii) classification of impacts and resource streams and (iii) characterisation of the magnitude of the impacts. The optional steps include valuation, which is the weighting of impacts and summation to a single index, grouping, normalization and data quality analysis.

3.3.1. Theory and Methodology

The aggregation of pollutants to total environmental burdens in the characterisation step is based on the concept of equivalency potentials. The impact scores for a category are generally calculated according to the following formula (Tukker, 2000);

$$S_i =_{1-j} \sum \left(e_{ij} * E_j \right)$$

where S_i = score for impact category i; E_j = magnitude of environmental intervention j; and e_{ij} = equivalency factor.

For example, methyl chloroform destroys only 0.11 times as many ozone molecules before being removed from the stratosphere as CFC 11 ($CFCl_3$), so it is assigned an ozone depletion potential (ODP) of 0.11, this is also known as the equivalency factor. All ozone depleting substances are multiplied by their ODP and then summed up to give the total pollution load in CFC 11 equivalents.

The GaBi 3 software package, which uses the CML (Centre for Environmental Science, University of Leiden, The Netherlands) LCA methodology (Heijungs et al., 1992), was used to compile environmental impact scores for each impact category. There are generally three classes of LCA software (Rebitzer el al., 2004);

- Generic LCA software, typically intended for use by researchers, consultants and other LCA specialists.
- Specialised LCA based software of various types for specific decision makers, typically intended for use by designers in engineering or construction, the purchasing department, or environmental or waste managers.
- Tailored LCA software systems to be used for clearly defined applications in specific IT environments.

The GaBi software that was used for this study falls into the first category; however it does also have some tools which allow it to be used for basic economic evaluations.

3.3.2. Assumptions

The selection of the impact categories for the LCA study depend on the purpose of the environmental problems towards which the system under study contributes, should be investigated. Categories have to be chosen in accordance with the goal and scope of the study in order to describe all the impacts caused by the processes under consideration. Lindfors et al. (1995) suggests a few issues to be taken into consideration when choosing environmental impact categories. These issues are:

- completeness (all relevant environmental problems should be covered),
- practicality (it is not practical to have too many categories),
- independence (mutually independent categories should be selected to avoid double counting of impacts – e.g. nitrogen oxides contributing to both acidification and nutrification) and
- relation to the characterisation step (for the categories selected there should be characterisation models available for the next step of the impact assessment).

The most important impact categories used in the literature are enumerated as follows:

- abiotic resource consumption,

- biotic resource consumption (sometimes refered to as renewable and non-renewable resources),
- land use,
- global warming potential,
- stratospheric ozone depletion potential,
- photochemical oxidant formation potential,
- ecotoxicological impacts (aquatic and terrestrial),
- human toxicological impacts,
- acidification potential,
- eutrophication potential,
- waste (sometimes a special category, hazardous waste, is defined) and
- work environment.

Not all categories have to be used in an LCA. In the present study, for example, land use is of less relevance. The software used also influences the choice of categories. Some LCA software tools have predefined categories; however, others allow the researcher to define their own category system. The GABI 3 software tool has predefined categories.

It was decided than when considering the environmental impacts eight impact categories would be considered. The impact categories were chosen based on their relevance in a South African context and the fact that for all these categories there is some sort of general consensus, amongst international researcher, regarding classification and characterisation. The selected categories are global warming, ozone depletion potential, acidification potential, eutrophication potential, photo-oxidant potential, aquatic ecotoxicity, terrestrial ecotoxicity and human ecotoxicity. Other researchers (Friedrich,2001 and Emmerson et al., 1995) have shown that these impact categories provide an accurate description of the environmental issues related to water and wastewater treatment. An explanation of each category follows;

Global warming: Heat is trapped in the atmosphere by the infrared adsorption of reflected sunlight. Anthropogenic emissions contribute significantly to increasing this adsorption capacity. Carbon dioxide, methane and nitrous oxide are all examples of greenhouse gases. The results are presented in terms of carbon dioxide equivalents. The effect of carbon dioxide as a greenhouse gas was modelled over a one hundred year time period.

Ozone depletion potential: Ozone depletion potential refers to the loss of ultraviolet absorption capacity through the destruction of ozone in the stratosphere. Ozone depletion potentials express the ozone depleting capacity of chloroflurocarbons (CFCs), hydrochloroflourocarbons (HCFCs) and halons relative to the reference substance CFC-11.

Acidification potential: This refers to an increase in acidity in water and soil systems. The characterisation factors express an emission in terms of sulphur dioxide equivalents.

Eutrophication potential: This category includes both aquatic and terrestrial eutrophication potentials. Aquatic eutrophication is the result of nutrient enrichment in aquatic environments. Terrestrial eutrophication is associated with the nutrient enrichment of soils. The characterisation factor expresses the eutrophication potential in terms of phosphate equivalents.

Photo-oxidant potential: Photochemical oxidant creation refers to the mixture of ozone and intermediate reaction products, such as peroxyacetyl nitrate (PAN), that are formed in the lower atmosphere under the influence of solar radiation in the visible and near-UV spectral ranges. The photo-chemical oxidation process depends on the presence of nitrogen oxides, OH-reactive hydrocarbon and carbon monoxide (Pennington, 2004). The characterisation factors express these chemicals in terms of ethane equivalents.

Aquatic, terrestrial and human ecotoxicity: An ecotoxicological effect is an adverse change in the structure, or function, of a species as a result of exposure to a chemical. The characterisation factor used is 1-4 dichlorobenzene (DCB).

There are numerous other impact categories which have been developed for use in the LCA methodology. These include, salinity, abiotic and biotic resource depletion and land use impacts, however this study was restricted to the above mentioned categories as they where deemed most relevant..

3.3.3. Results

The results of the LCIA were calculated and are presented in this section.

3.3.3.1. Inanda Dam

The life cycle of a dam consists of three stages: construction, operation and decommissioning. All these stages have different inputs and outputs contributing towards the total environmental burden of the dam. In the construction stage fossil fuel (diesel) is used by the earth-moving equipment and concrete and steel are used in the structures of the dam. Taking into account these inputs, LCA scores can be calculated for the construction of a dam. For the operation stage, however, the inputs and outputs are significant for only one impact category, namely global warming.

The contribution from the construction and decommissioning stages is also relatively minor. Therefore this section only considers the impacts from global warming. A full discussion of the impacts related to Inanda dam is presented in Appendix 1. This appendix also considers impacts that fall outside the selected impact categories.

It has been discovered that important amounts of greenhouse gases (carbon dioxide and methane) are emitted from dams (Louis et al., 2000). These gases are produced by aerobic (carbon dioxide) and anaerobic (carbon dioxide and methane) decomposition. Louis (2000) and his team at the University of Alberta estimated that reservoirs worldwide release 70 million tons of methane and around a billion tons of carbon dioxide annually. Reservoir releases of the two gases combined contribute to an estimated seven percent of the global warming impact of other human activities calculated over a 100 year period.

It is accepted that during the first seven years from the time of the filling of the dam, 25% of the total methane emitted by the dam will be released. This is due to the methane released from the decomposition of the tress and grassland that is submerged. Thereafter emissions are from the decomposition of organics entering and growing in the dam. (Rosa, 2000) In the oxic layer of water, CO_2 is produced by aerobic decomposition of dissolved and particulate organic carbon (DOC, POC) and methane as it diffuses up from the lower strata. In the anoxic layer organic matter is decomposed by methanogenesis, CH_4 and CO_2 result. (Rosa, 2002)

The Brazilian model was chosen as the temperature profiles of the Brazilian dams studied closely match the temperature profile of Inanda dam. In a colder climate such as Canada, it is estimated that it takes 50 years for 60% of the submerged biomass to decompose. During this period only 5-10% of the carbon would undergo anaerobic decomposition and release methane. (Rudd et al (1993))

The total organic carbon (TOC) entering the dam is 4.50 mg/l and the TOC leaving the dam is 3.35 mg/l (Terry, 2004). Using the Brazilian estimate that 10-30% (Rosa, 2002) of the entering TOC is converted to methane and the rest to carbon dioxide it was calculated that a worst case estimate of the emissions of greenhouse gases from Inanda Dam were 0.047 kg/kl CO_2 equivalents. This method of calculating dam emissions is similar to that use by Liikanen (2002) and is a useful tool to get an estimate to use for order of magnitude calculations. The detailed calculations and the relevant assumptions and literature are presented in greater detail in Appendix 1.

3.3.3.2. Wiggins Waterworks

Construction

The impacts from the construction phase are due to two sources. The production of the concrete and the transport of the materials used for the concrete. Since the transport distances are small the impacts from the transport are negligible and the bulk of the impacts are due to the production of the concrete.

Some data on the production of cement had to be estimated since all the required emissions data are not measured. However it soon became obvious that the construction stage is of secondary importance and hence further detailed time consuming investigations have not been carried out to gather this data. Table 3-18 presents the environmental burdens associated with the construction stage.

Table 3-18: Environmental profile of Wiggins Waterworks for the construction stage (Friedrich, 2000).

Impact category	Construction
Global Warming (kg CO2 eq)	1.14E-02
Ozone depletion (kg R11 eq)	3.90E-10
Acidification (kg SO2 eq)	7.81E-05
Eutrophication (kg Phosphate eq)	8.47E-06
Photo-oxidant (kg ethene eq)	2.48E-06
Aquatic ecotoxicity (kg DCB eq)	6.25E-05
Terrestrial ecotoxicity (kg DCB eq)	2.73E-02
Human ecotoxicity (kg DCB eq)	7.39E-04

Operations

In the production of potable water the main inputs are electricity and the chemicals used. These chemicals are calcium hypochlorite, molecular chlorine, sodium hypochlorite, polymeric coagulant, slaked lime, activated carbon and molecular oxygen. Table 3-19 presents the environmental burdens associated with the operations stage.

Table 3-19: Environmental profile of Wiggins Waterworks for the operations stage (Friedrich, 2000).

Impact category	Operations
Global Warming (kg CO2 eq)	1.73E-01
Ozone depletion (kg R11 eq)	3.21E-09
Acidification (kg SO2 eq)	1.02E-03
Eutrophication (kg Phosphate eq)	6.55E-05
Photo-oxidant (kg ethene eq)	1.32E-05
Aquatic ecotoxicity (kg DCB eq)	2.66E-03
Terrestrial ecotoxicity (kg DCB eq)	2.31E-01
Human ecotoxicity (kg DCB eq)	3.31E-03

Decommissioning

Data for the decommissioning phase was obtained from the existing information on decommissioning of waterworks by Umgeni Water. The two major assumptions were that all materials which can be recycled will be recycled and that if tanks cannot be used for other purposes they will be filled in with soil and the area revegetated. Table 3-20 presents the environmental burdens associated with the decommissioning phase.

Table 3-20: Environmental profile of Wiggins Waterworks for the decommissioning stage (Friedrich, 2000).

Impact category	Decommissioning
Global Warming (kg CO2 eq)	1.48E-04
Ozone depletion (kg R11 eq)	9.16E-12
Acidification (kg SO2 eq)	4.92E-07
Eutrophication (kg Phosphate eq)	4.30E-08
Photo-oxidant (kg ethene eq)	5.67E-08
Aquatic ecotoxicity (kg DCB eq)	1.52E-06
Terrestrial ecotoxicity (kg DCB eq)	5.85E-04
Human ecotoxicity (kg DCB eq)	3.75E-05

3.3.3.3. Pumping and Reticulation Network

Distribution

The scores for the impact categories of this LCA have been calculated in the same manner as those for Wiggins Waterworks and are presented in Table 3-21.

Table 3-21: Environmental scores for the distribution of potable water (per kl billed to the consumers)

Impact Category	Pipes	Electricity	Total
Global Warming (kg CO2 eq)	0.0559 (28.6%)	0.1391 (71.4%)	0.1950
Ozone depletion (kg R11 eq)	2.28E-9 (46.3%)	2.63E-9 (53.7 %)	4.90E-9
Acidification (kg SO2 eq)	0.00032 (28.8 %)	0.00079 (71.2 %)	0.00111
Eutrophication (kg Phosphate eq)	3.26E-5 (38.6 %)	5.18E-5 (61.4 %)	8.44E-5
Photo-oxidant (kg ethene eq)	13.2E-6 (57.2 %)	9.88E-6 (42.8 %)	23.1E-6
Aquatic ecotoxicity (kg DCB eq)	0.0004 (15.4 %)	0.0022 (84.6 %)	0.0026
Terrestrial ecotoxicity (kg DCB eq)	0.1659 (47 %)	0.1870 (53 %)	0.3529
Human ecotoxicity (kg DCB eq)	0.0045 (62.5 %)	0.0027 (37.5 %)	0.0072

Table 3-21 shows that the energy requirements due to pumping and the use of electricity dominate the environmental scores for the distribution of water in the studied area. Only for two assessment categories, namely photo-oxidant (smog) formation and human toxicity, are the scores for pipes higher than those for pumping. At closer look the photo-oxidant formation and human toxicity due to pipes is traced back to the manufacture of steel used in the steel pipes. The values in this table have not been normalised, nor can they be combined into a single environmental score.

The degree of error in the calculation of these scores is considered to be low, since the data on the inputs are considered to be good with regard to relevance and completeness. The only shortcoming is with regard to the mining process of asbestos (included in the asbestos cement pipes) where quantitative data on the toxicity of this substance were not obtained. In particular, the toxicity to the workers mining the mineral was not considered and this is a public issue in South Africa.

Collection

Using the material inputs and the energy figure for the pumping of wastewater LCA scores have been calculated for the collection and transport of wastewater from the customers to the waterworks. These scores are presented in Table 3-22.

Table 3-22: Environmental scores for the collection of wastewater (per kl of wastewater)

Impact Category	Pipes and Manholes	Electricity	Total
Global Warming (kg CO2 eq)	0.0285 (16%)	0.1498 (84%)	0.1783
Ozone depletion (kg R11 eq)	0 (0 %)	2.83E-9 (100 %)	2.83E-9
Acidification (kg SO2 eq)	0.0003 (26 %)	0.00085 (74 %)	0.00115
Eutrophication (kg Phosphate eq)	3.33E-5 (37.4 %)	5.57E-5 (62.6 %)	8.90E-5
Photo-oxidant (kg ethene eq)	0.06E-5 (5.4 %)	1.06E-5 (94.6 %)	1.12E-5
Aquatic ecotoxicity (kg DCB eq)	0.0001 (4.2 %)	0.0023 (95.8 %)	0.0024
Terrestrial ecotoxicity (kg DCB eq)	0.0002 (0.01 %)	0.2014 (99.9 %)	0.2016
Human ecotoxicity (kg DCB eq)	0.0001 (3.3 %)	0.0029 (96.7 %)	0.0030

From Table 3-22 it is evident that the LCA scores for the collection of wastewater in the area studied are also dominated by the electricity required for pumping. In the calculation of these scores the degree of error is considered to be medium, since the quality of the data on which the scores are based are only partially good. The data for the manufacture of vitrified clay pipes and cement are not complete with regard to the emissions that contribute towards toxicity (aquatic, terrestrial and human).

3.3.3.4. Southern Wastewater Treatment Works

The results from the Southern Wastewater Treatment Works are presented in terms of the primary and secondary treatment plants.

Primary treatment - Construction

The impacts for the construction phase are directly proportional to the mass of concrete used in the construction of each unit. Table 3-23 presents the environmental impacts from the construction phase of the primary treatment plant.

Table 3-23: Environmental profile of the primary treatment plant and the individual units for the construction stage.

Impact category	**Primary Total**	Inlet works	Screen/degrit	Screw pump	Elevated channel	PST
Global Warming (kg CO2 eq)	1.32E-03	8.86E-05	2.27E-04	1.27E-04	2.70E-04	6.06E-04
Ozone depletion (kg R11 eq)	5.59E-11	3.26E-12	8.43E-12	1.15E-11	9.93E-12	2.26E-11
Acidification (kg SO2 eq)	8.01E-06	5.42E-07	1.39E-06	7.03E-07	1.65E-06	3.70E-06
Eutrophication (kg Phosphate eq)	8.26E-07	5.69E-08	1.45E-07	6.07E-08	1.73E-07	3.88E-07
Photo-oxidant (kg ethene eq)	3.05E-07	1.95E-08	4.98E-08	4.14E-08	5.93E-88	1.34E-07
Aquatic ecotoxicity (kg DCB eq)	8.23E-06	5.48E-07	1.40E-06	8.46E-07	1.67E-06	3.75E-06
Terrestrial ecotoxicity (kg DCB eq)	3.62E-03	2.38E-04	6.08E-04	4.13E-04	7.24E-04	1.63E-03
Human ecotoxicity (kg DCB eq)	9.61E-05	6.46E-06	1.65E-05	9.09E-06	1.96E-05	4.41E-05

The input to each unit is relatively the same, therefore the proportion of impacts for all the categories will also be similar. There are two primary settling tanks and the largest volume of concrete is used for these units. Therefore almost 45% of the impacts for the construction stage come from the primary settlers. The other impacts can be traced roughly as follows; inlet works, 7%; screen degrit, 17%; raw screw pumps, 11%; and the elevated channel, 20%.

Table 3-24 has been included to show where impacts attributed to the construction of the civil works stem from. The aluminium is used in the pumps that have been included in the construction stage. The steel sheet is used mainly in the reinforcing steel and to a small extent in the pump construction. As can be seen, most of the impacts are associated with the production of the steel used in the construction. Cement production also features in three categories; global warming, acidification and eutrophication potential. Diesel used for the mining of the raw materials used in the production of concrete has a negligible contribution.

Table 3-24: Contributions to the total environmental impacts for the primary treatment plant from each input for the construction stage. Contributions to the total are shown in parenthesis.

Impact category	Primary	Aluminium	Cement	Diesel	Steel sheet
Global Warming (kg CO2 eq)	1.32E-03	2.69E-05 (2%)	5.49E-04 (42%)	2.42E-06 (0%)	7.43E-04 (56%)
Ozone depletion (kg R11 eq)	5.59E-11	7.47E-12 (13%)	0.00E+00 (0%)	0.00E+00 (0%)	4.84E-11 (87%)
Acidification (kg SO2 eq)	8.01E-06	1.67E-07 (2%)	5.61E-06 (70%)	1.47E-08 (0%)	2.21E-06 (28%)
Eutrophication (kg Phosphate eq)	8.26E-07	5.82E-09 (1%)	6.43E-07 (78%)	1.73E-09 (0%)	1.75E-07 (21%)
Photo-oxidant (kg ethane eq)	3.05E-07	1.69E-08 (6%)	0.00E+00 (0%)	1.75E-08 (6%)	2.71E-07 (89%)
Aquatic ecotoxicity (kg DCB eq)	8.23E-06	1.13E-07 (1%)	0.00E+00 (0%)	4.68E-09 (0%)	8.12E-06 (99%)
Terrestrial ecotoxicity (kg DCB eq)	3.62E-03	9.69E-05 (3%)	0.00E+00 (0%)	3.86E-06 (0%)	3.52E-03 (97%)
Human ecotoxicity (kg DCB eq)	9.61E-05	4.65E-07 (0%)	1.63E-06 (2%)	2.78E-08 (0%)	9.40E-05 (98%)

Primary treatment -Operations

As stated previously, the only input to the operations stage is electricity. Thus all the impacts can be traced to the generation of electricity. The burdens associated with each unit are directly proportional to the amount of electricity used by each process. Thus the raw sewage screw pumps largely dominate the profile of the operational stage for the primary treatment works. The split for all the impact categories is the same with 98% of the impacts coming from electricity used by the screw pumps and only 2% from the primary settlers.

Table 3-25 presents the contributions from the operation stage for each process.

Table 3-25: Contributions to the total environmental impacts for the primary treatment plant from each individual process for the operations stage.

Impact category	Primary	PST	RS pumps
Global Warming (kg CO2 eq)	1.12E-01	2.20E-03	1.10E-01
Ozone depletion (kg R11 eq)	2.12E-09	4.16E-11	2.08E-09
Acidification (kg SO2 eq)	6.41E-04	1.26E-05	6.28E-04
Eutrophication (kg Phosphate eq)	4.10E-05	8.04E-07	4.02E-05
Photo-oxidant (kg ethene eq)	7.97E-06	1.56E-07	7.82E-06
Aquatic ecotoxicity (kg DCB eq)	1.79E-03	3.51E-05	1.76E-03
Terrestrial ecotoxicity (kg DCB eq)	1.51E-01	2.96E-03	1.48E-01
Human ecotoxicity (kg DCB eq)	2.23E-03	4.37E-05	2.19E-03

3.3.3.5. Decommissioning

As decommissioning has such a small contribution to the life cycle burden of the recycling process, this stage was not investigated in very great detail. Table 3-26 shows the impacts associated with the decommissioning of the plant.

Table 3-26: Contributions to the total environmental impacts for the primary treatment plant for the decommissioning stage.

Impact category	Primary
Global Warming (kg CO2 eq)	4.58E-05
Ozone depletion (kg R11 eq)	0.00E+00
Acidification (kg SO2 eq)	3.92E-07
Eutrophication (kg Phosphate eq)	6.32E-08
Photo-oxidant (kg ethene eq)	7.96E-08
Aquatic ecotoxicity (kg DCB eq)	1.16E-08
Terrestrial ecotoxicity (kg DCB eq)	9.58E-06
Human ecotoxicity (kg DCB eq)	1.93E-07

As explained in the LCI stage the impacts for this stage come from the diesel used in transporting the concrete structures to a landfill site and the metals used in the pumps to a recycling facility. As the recycling is not done in South Africa and the impacts associated with this stage are small in relation to the entire life cycle this process was not included in the scope of this study.

Secondary Treatment

As previously discussed the impacts will be discussed in terms of the construction, operation and decommissioning. In this section the activated sludge and clarifiers will be looked at separately so that one can get a picture of the impacts associated with each process.

Secondary treatment - Construction

The unit operations will be considered individually and then combined to create a picture of the secondary treatment plant. The results of the impact assessment of the construction stage of the secondary treatment plant are presented in Table 3-27.

Table 3-27: Environmental profile of the secondary treatment plant and the individual units for the construction stage.

Impact category	Secondary	Activated sludge	Clarifiers
Global Warming (kg CO2 eq)	3.34E-03	2.10E-03	1.24E-03
Ozone depletion (kg R11 eq)	1.24E-10	7.81E-11	4.56E-11
Acidification (kg SO2 eq)	2.04E-05	1.28E-05	7.55E-06
Eutrophication (kg Phosphate eq)	2.14E-06	1.35E-06	7.92E-07
Photo-oxidant (kg Ethene eq)	7.35E-07	4.64E-07	2.72E-07
Aquatic ecotoxicity (kg DCB eq)	2.07E-05	1.30E-03	7.64E-06
Terrestrial ecotoxicity (kg DCB eq)	8.97E-03	5.66E-03	3.32E-03
Human ecotoxicity (kg DCB eq)	2.43E-04	1.53E-04	9.00E-05

The impacts can be traced to four processes; production of aluminium, steel, diesel and cement as explained in the discussion of the primary treatment process. Table 3-28 shows this.

Table 3-28: Contributions to the total environmental impacts for the secondary treatment plant from each input for the construction stage.

Impact category	Secondary	Aluminium	Cement	Diesel	Steel sheet
Global Warming (kg CO2 eq)	3.34E-03	2.58E-06	1.44E-03	6.36E-06	1.89E-03
Ozone depletion (kg R11 eq)	1.24E-10	7.15E-13	0.00E+00	0.00E+00	1.23E-10
Acidification (kg SO2 eq)	2.04E-05	1.60E-08	1.47E-05	3.86E-08	5.63E-06
Eutrophication (kg Phosphate eq)	2.14E-06	5.57E-10	1.69E-06	4.55E-09	4.46E-07
Photo-oxidant (kg ethene eq)	7.35E-07	1.62E-09	0.00E+00	4.58E-08	6.88E-07
Aquatic ecotoxicity (kg DCB eq)	2.07E-05	1.08E-08	0.00E+00	1.23E-08	2.06E-05
Terrestrial ecotoxicity (kg DCB eq)	8.97E-03	9.27E-06	0.00E+00	1.01E-05	8.96E-03
Human ecotoxicity (kg DCB eq)	2.43E-04	4.45E-08	4.28E-06	7.29E-08	2.39E-04

Operations

The only input to the operations stage is electricity and therefore all impacts associated with this stage can be traced to the generation of electricity. These impacts are shown in the table below.

Table 3-29: Contributions to the total environmental impacts for the secondary treatment plant from each individual process for the operations stage.

Impact category			
	Secondary	Activated sludge	Clarifiers
Global Warming (kg CO2 eq)	2.97E-01	2.97E-01	4.40E-03
Ozone depletion (kg R11 eq)	5.62E-09	5.62E-09	8.32E-11
Acidification (kg SO2 eq)	1.70E-03	1.70E-03	2.51E-05
Eutrophication (kg Phosphate eq)	1.09E-04	1.08E-04	1.61E-06
Photo-oxidant (kg ethene eq)	2.11E-05	2.11E-05	3.13E-07
Aquatic ecotoxicity (kg DCB eq)	4.75E-03	4.74E-03	7.03E-05
Terrestrial ecotoxicity (kg DCB eq)	4.00E-01	4.00E-01	5.92E-03
Human ecotoxicity (kg DCB eq)	5.90E-03	5.90E-03	8.74E-05

As can be seen from the above table most of the impacts are from the activated sludge process. This is easily explained by the fact that this process uses 0.99MJ/kl water produced as opposed to 0.0146MJ/kl for the clarifiers. As stated the impacts associated with electricity will be discussed further in chapter 4.

Decommissioning

As decommissioning has such a small contribution to the life cycle burden of the recycling process, this stage was not investigated in very great detail.

Table 3-30: Contributions to the total environmental impacts for the secondary treatment plant for the decommissioning stage.

Impact category	
	Decommissioning
Global Warming (kg CO2 eq)	1.20E-04
Ozone depletion (kg R11 eq)	0.00E+00
Acidification (kg SO2 eq)	1.02E-06
Eutrophication (kg Phosphate eq)	1.65E-07
Photo-oxidant (kg ethene eq)	2.08E-07
Aquatic ecotoxicity (kg DCB eq)	3.03E-08
Terrestrial ecotoxicity (kg DCB eq)	2.49E-05
Human ecotoxicity (kg DCB eq)	5.04E-07

The impacts for this stage come from the diesel used in transporting the concrete structures to a landfill site and the metals used in the pumps to a recycling facility.

3.3.3.6. Durban Water Recycling

Tangsubkul et al. (2001) identified a number of common and specific issues for non-potable water recycling and these are presented in Table 3-31 .

Table 3-31: Major issues in water recycling (Tangsubkul et al., 2001)

Issues in water recycling		
Common issues to all applications		*Additional issues for non-potable water recycling*
Technical	Appropriate advanced treatment technology	Removal of nutrient
	Reliability	
	Retrofitability	
Environmental	Use of renewable energy	Nutrient recycling (N&P)
	Space requirement	Soil salinity
	Eutrophication	Reaction of vegetation towards soil and water
		Heavy metals accumulation
Health	Acute health impact	Persistence of viruses in irrigated crops
	Chronic health impact	Persistence of toxic substances in irrigated crops
	Unknown health impact	
Economic	Installation costs	
	Operation and maintenance costs	
Social	Source control of chemical additives in wastewater stream	Build up of salts in soils

LCA does not focus on all these issues and many are largely irrelevant to this sub-system due to the disposal of sludge to sea. However what is important is for the designer of a recycling process to be aware of all these important issues. The LCA shows how the environmental impacts are interconnected to these issues.

Tertiary treatment - Construction

The impacts are directly proportional to the mass of concrete used in the construction of each unit. Table 3-32 presents the impacts from the construction phase from each unit.

Table 3-32: Environmental profile of the tertiary treatment plant and the individual units for the construction stage

Impact category	Tertiary	Settlers	Dual Media	Ozonators	GAC	Chlorinators
Global Warming (kg CO2 eq)	6.55E-03	1.72E-03	9.16E-04	5.69E-04	1.64E-03	1.71E-03
Ozone depletion (kg R11 eq)	2.43E-10	6.48E-11	3.69E-11	2.09E-11	6.05E-11	6.31E-11
Acidification (kg SO2 eq)	4.00E-05	1.05E-05	5.58E-06	3.48E-06	1.00E-05	1.05E-05
Eutrophication (kg Phosphate eq)	4.19E-06	1.10E-06	5.79E-07	3.65E-07	1.05E-06	1.10E-06
Photo-oxidant (kg ethene eq)	1.44E-06	3.81E-07	2.08E-07	1.25E-07	3.61E-07	3.77E-07
Aquatic ecotoxicity (kg DCB eq)	4.05E-05	1.07E-05	5.68E-06	3.51E-06	1.02E-05	1.06E-05
Terrestrial ecotoxicity (kg DCB eq)	1.76E-02	4.64E-03	2.49E-03	1.53E-03	4.41E-03	4.60E-03
Human ecotoxicity (kg DCB eq)	4.77E-04	1.25E-04	6.65E-05	4.14E-05	1.20E-04	1.25E-04

Although the lamellae settlers and the dual media filters are relatively the same size the contribution from the settlers to the environmental profile for the construction phase is almost twice that of the filters. This is due to the fact that the backwash pumps and blowers were grouped with the settlers although both units share these. The contribution from the settlers is approximately 26% while the contribution from the filters is 13%. Note that the settlers also have a large motor which drives a scraper at the bottom associated with them. The rest of the contributions come from the activated carbon filters (25%), the chlorinators (25%) and the chlorinators (9%).

Tertiary treatment - Operations

Table 3-33 shows the contributions from each process in the tertiary treatment plant to the operations stage.

Table 3-33: Contributions to the total environmental impacts for the tertiary treatment plant from each individual process for the operations stage.

Impact category	Tertiary	Settlers	Dual Media	Ozonators	GAC	Chlorinators
Global Warming (kg CO2 eq)	9.42E-02	3.67E-02	9.01E-04	4.57E-02	9.01E-04	9.68E-03
Ozone depletion (kg R11 eq)	2.95E-09	2.04E-09	1.70E-11	8.65E-10	1.70E-11	0.00E+00
Acidification (kg SO2 eq)	5.26E-04	1.17E-04	5.14E-06	2.61E-04	5.14E-06	1.36E-04
Eutrophication (kg Phosphate eq)	3.05E-05	5.82E-06	3.29E-07	1.67E-05	3.29E-07	7.28E-06
Photo-oxidant (kg ethene eq)	8.63E-06	5.00E-06	6.40E-08	3.25E-06	6.40E-08	7.30E-07
Aquatic ecotoxicity (kg DCB eq)	9.64E-04	2.01E-04	1.44E-05	7.30E-04	1.44E-05	0.00E+00
Terrestrial ecotoxicity (kg DCB eq)	1.07E-01	4.29E-02	1.21E-03	6.15E-02	1.21E-03	0.00E+00
Human ecotoxicity (kg DCB eq)	1.30E-03	3.18E-03	1.79E-05	9.08E-04	1.79E-05	2.99E-05

For the operations stage of the tertiary treatment plant the impacts come from the chemical and electrical inputs to the processes. For a unit like the ozonation unit all the impacts can be attributed to the electrical input whereas for the lamellae settlers the contribution from electricity is negligible with most of the impacts coming from the chemical inputs.

Tertiary treatment - Decommissioning

Table 3-34 shows the environmental impacts associated with decommissioning the plant. The decommissioning procedure is exactly the same as discussed for the primary and secondary plants.

Table 3-34: Contributions to the total environmental impacts for the tertiary treatment plant for the decommissioning stage.

Impact category	Tertiary
Global Warming (kg CO2 eq)	2.36E-04
Ozone depletion (kg R11 eq)	0.00E+00
Acidification (kg SO2 eq)	2.02E-06
Eutrophication (kg Phosphate eq)	3.26E-07
Photo-oxidant (kg ethene eq)	4.10E-07
Aquatic ecotoxicity (kg DCB eq)	5.97E-08
Terrestrial ecotoxicity (kg DCB eq)	4.92E-05
Human ecotoxicity (kg DCB eq)	9.93E-07

3.3.3.7. Durban Southern Deep Sea Outfall

Since the effluent discharged from the marine outfall is a complex mixture of domestic and selected industrial effluents, chemical analyses of these effluents can never satisfactorily cover all the possible constituents and the combined effect on the environment. It was therefore decided to use the sea urchin toxicity testing method to measure the toxicity of the effluents being discharged. This is the method is currently in use by the Durban Metro to monitor the sea outfall. However it was necessary to modify the test procedure to make it compatible with the LCA methodology.

Samples were also taken at various points in the wastewater works, recycling plant and the sea outfall to see how the toxicity changes after each process unit. A detailed description of the toxicity testing procedure and analysis is presented in Appendix 2.

Since the flow of the effluent to sea is by gravity there is no energy input for this stage. Also since the pipeline is designed to last for a period of 70 years it is expected that the impacts of the construction and decommissioning of the pipeline will have a negligible impact. Thus the majority of the impacts are due to the toxicity of the effluent from the pipeline during operation. This will fall under the impact category of aquatic ecotoxicity.

As explained earlier in Section 3-3-2, aquatic ecotoxicity is measured in kilograms of dichlorobenzene (DCB) equivalents. Experiments (described in Appendix 2) were set up to convert the current sea urchin testing method data to DCB equivalents. The toxicity of the effluent being discharged to sea was calculated as being 4.2E-04 kg DCB equivalents per kilolitre of effluent pumped to sea.

3.4. Interpretation

3.4.1. Theory and Methodology

Interpretation is the fourth phase in an LCA. The aim of this phase is to reduce the amount of quantitative and qualitative data gathered during an LCA study to a number of key issues, which will be usable in a decision making process. However, this reduction should give an acceptable coverage and representation of the previous phases in an LCA. The development of Life Cycle Interpretation was driven from the needs of the users before the background of the problem of how to handle the findings from today's LCAs. The interpretation step was developed to provide answers to questions like, "What does this difference mean?", "How reliable are the results?" and "Are the findings made in accordance with the Goal and Scope?"(Saur K, 1997)

The three principle steps of the interpretation according to the ISO 14043 standard are: identification of the significant issues based on the inventory and impact assessment phases of the LCA, evaluation (completeness, sensitivity and consistency checks) and conclusions, recommendations and reporting. The sensitivity analyses will be dealt with in the next chapter which also considers different scenarios.

3.4.2. Results

This section discusses the results from the impact analysis.

3.4.2.1. Inanda Dam

The net emissions from the dam are constant regardless of the amount of water abstracted. This is due to the relationship between the surface area of the dam and the net emissions (Rosa, 2000). Thus in seeking to lower the emissions per kilolitre water abstracted it would make sense to use the dam at its maximum abstraction rate if possible, otherwise the dam just serves as a large storage vessel giving off emissions of GHGs. As stated earlier in Section 3.2 the LCA study focuses on the greenhouse gas emissions of Inanda dam. The first question an LCA practitioner must ask when doing an improvement analysis is, how significant are the impacts one is trying to reduce. Figure 3-2 presents the specific emissions of Inanda dam for a range of abstraction rates. As expected the emissions per kilolitre will decrease as the dam is operated at increasing abstraction rates up to its maximum abstraction rate. The emissions from the operations phase of Wiggins Waterworks and the primary and secondary treatment plants are relatively constant per kilolitre treated. The dam is currently operated at an average of 220 ML/day. It can be seen that there will only be a small gain by operating the dam at its maximum capacity. The graph also puts into perspective the magnitude of the dam's emissions. Even when the dam is being operated at an extremely low abstraction level of 25 ML/day the relative impact of the dam is small. The top line of the graph shows the combined operational burden of the dam and the rest of the system. This is an approximation as the functional units are not the same.

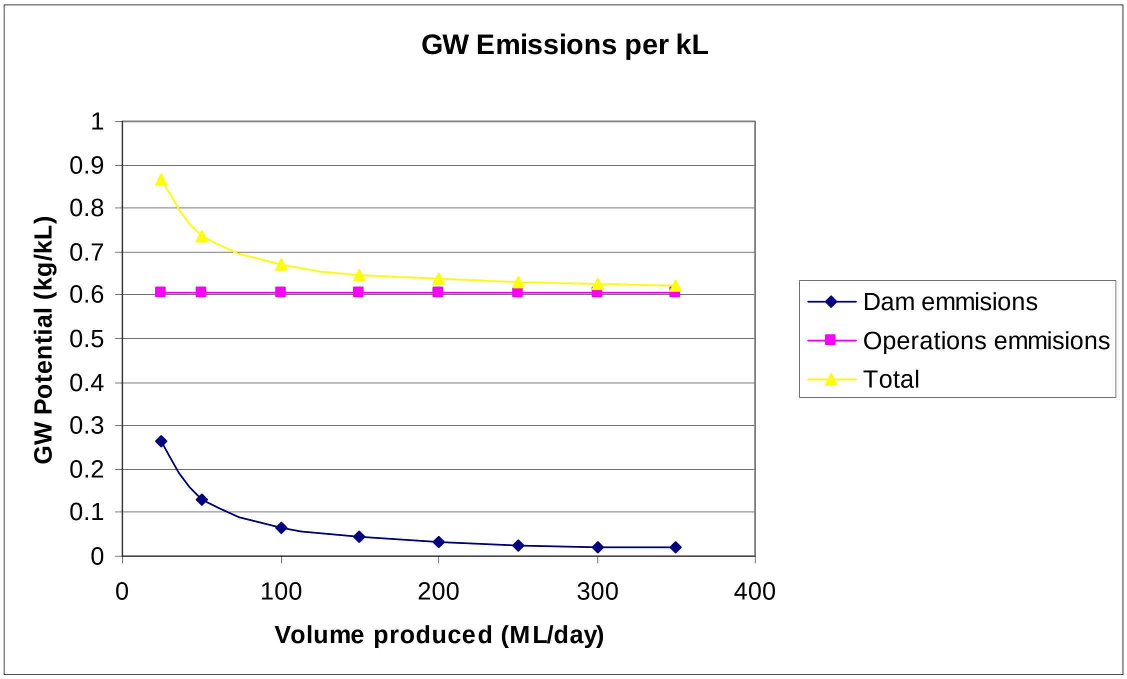

Figure 3-3: Global warming emissions per kilolitre water abstracted from Inanda Dam for the operations phase. Also shown are the emissions for the operations phase of the rest of the system.

However when one looks at operating the dam at an even lower abstraction level, in other words using the dam as a storage tank (this would occur in the case of a decommissioned dam which is used solely for recreation purposes), the impact of the dam increases.

Figure 3-3 indicates two important things. Firstly the impact of the dam per kilolitre per day abstracted is relatively small compared to the operational emissions from the rest of the system provided the dam is operated at an abstraction rate of over 150 ML/day (the dam's contribution is then less than 5 %) and secondly, if the dam is not producing water and is used mainly as a storage tank hence functioning as a lake then it is an massive emitter of greenhouse gases with no return.

Figure 3-4 shows how compared to the operations phase of the downstream units the total emissions from the dam are relatively small.

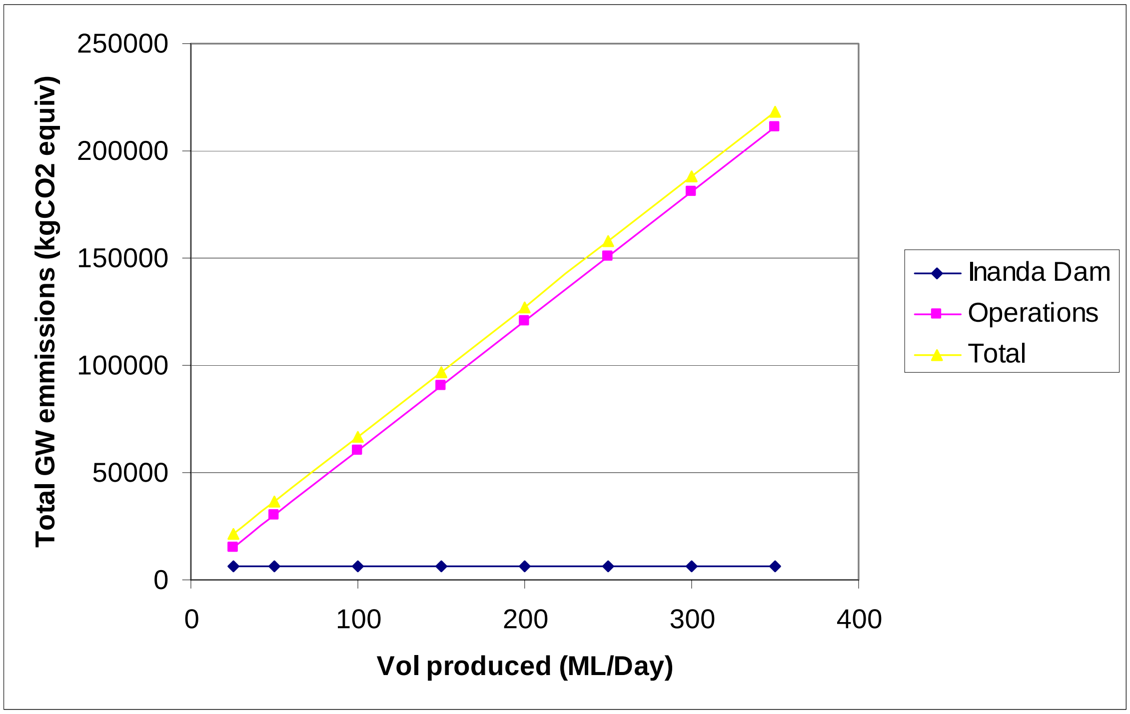

Figure 3-4: Total emissions from the operations phase of the system, the operations phase of Inanda dam and the combined emissions.

3.4.2.2. Wiggins Waterworks

Overall Environmental Profile

The overall environmental score is made up by the summation of the scores for the individual life cycle stages, i.e. construction of operation units, production of potable water and decommissioning of the operation units. Table 3-35 presents the scores for these stages and their proportion to the overall score.

Table 3-35: Overall environmental profile of the Wiggins Waterworks, showing the contributions from the construction, operation and decommissioning stages. The percentage contribution from each stage is shown on parenthesis (based on Friedrich, 2000).

Impact category	Construction	Operation	Decommissioning	Total
Global Warming (kg CO2 eq)	1.14E-02 (6%)	**1.73E-01 (94%)**	1.48E-04 (0%)	1.85E-01
Ozone depletion (kg R11 eq)	3.90E-10 (11%)	**3.21E-09 (89%)**	9.16E-12 (0%)	3.61E-09
Acidification (kg SO2 eq)	7.81E-05 (7%)	**1.02E-03 (93%)**	4.92E-07 (0%)	1.10E-03
Eutrophication (kg Phosphate eq)	8.47E-06 (11%)	**6.55E-05 (89%)**	4.30E-08 (0%)	7.40E-05
Photo-oxidant (kg ethene eq)	2.48E-06 (16%)	**1.32E-05 (84%)**	5.67E-08 (0%)	1.57E-05
Aquatic ecotoxicity (kg DCB eq)	6.25E-05 (2%)	**2.66E-03 (98%)**	1.52E-06 (0%)	2.73E-03
Terrestrial ecotoxicity (kg DCB eq)	2.73E-02 (11%)	**2.31E-01 (89%)**	5.85E-04 (0%)	2.59E-01
Human ecotoxicity (kg DCB eq)	7.39E-04 (18%)	**3.31E-03 (81%)**	3.75E-05 (1%)	4.09E-03

From the percentage values in parenthesis it is clear that the operation stage has the most significant contribution for the overall environmental profile. For all the categories considered the contribution from this stage is greater than 80% with some of the categories such as aquatic ecotoxicity, global warming and acidification being greater than 90%.

3.4.2.3. Pumping and Reticulation Network

The environmental impact of the collection of wastewater is solely from the energy expended in pumping. The effects of power generation in South Africa will be discussed in chapter 4.

3.4.2.4. Southern Wastewater Treatment Works

Primary Treatment Plant – Overall

From the individual stages an overall profile was constructed. This includes the construction, operations and decommissioning stages.

Table 3-36: Overall environmental profile of the primary treatment plant, showing the contributions from the construction, operation and decommissioning stages. The percentage contribution from each stage is shown in parenthesis.

Impact category	Construction	Operation	Decommissioning	Total
Global Warming (kg CO2 eq)	1.32E-03 (1%)	**1.12E-01 (99%)**	4.58E-05 (0%)	1.14E-01
Ozone depletion (kg R11 eq)	5.59E-11 (3%)	**2.12E-09 (97%)**	0.00E+00 (0%)	2.18E-09
Acidification (kg SO2 eq)	8.01E-06 (1%)	**6.41E-04 (99%)**	3.92E-07 (0%)	6.49E-04
Eutrophication (kg Phosphate eq)	8.26E-07 (2%)	**4.10E-05 (98%)**	6.32E-08 (0%)	4.19E-05
Photo-oxidant (kg ethene eq)	3.05E-07 (4%)	**7.97E-06 (95%)**	7.96E-08 (1%)	8.36E-06
Aquatic ecotoxicity (kg DCB eq)	8.23E-06 (0%)	**1.79E-03 (100%**	1.16E-08 (0%)	1.80E-03
Terrestrial ecotoxicity (kg DCB eq)	3.62E-03 (2%)	**1.51E-01 (98%)**	9.58E-06 (0%)	1.55E-01
Human ecotoxicity (kg DCB eq)	9.61E-05 (4%)	**2.23E-03 (96%)**	1.93E-07 (0%)	2.33E-03

Table 3-37 shows that for the primary treatment plant almost all the impacts come from the operations stage. A closer examination of the contribution of the individual processes making up the primary treatment plant is given in Table 3-37.

Table 3-37: Environmental burdens of each unit operation in the primary treatment plant. Percentage contributions to the total environmental burden are shown in parenthesis.

Impact category	Inlet works	Screen/degrit	RS pumps	Elevated channel	PST	Total
Global Warming (kg CO2 eq)	8.86E-05 (0%)	2.27E-04 (0%)	**1.10E-01 (97%)**	2.70E-04 (0%)	2.81E-03 (2%)	1.14E-01
Ozone depletion (kg R11 eq)	3.26E-12 (0%)	8.43E-12 (0%)	**2.09E-09 (96%)**	9.93E-12 (0%)	6.43E-11 (3%)	2.18E-09
Acidification (kg SO2 eq)	5.42E-07 (0%)	1.39E-06 (0%)	**6.29E-04 (97%)**	1.65E-06 (0%)	1.63E-05 (3%)	6.49E-04
Eutrophication (kg Phosphate eq)	5.69E-08 (0%)	1.45E-07 (0%)	**4.02E-05 (96%)**	1.73E-07 (0%)	1.19E-06 (3%)	4.18E-05
Photo-oxidant (kg ethene eq)	1.95E-08 (0%)	4.98E-08 (1%)	**7.86E-06 (95%)**	5.93E-08(1%)	2.90E-07 (4%)	8.28E-06
Aquatic ecotoxicity (kg DCB eq)	5.48E-07 (0%)	1.40E-06 (0%)	**1.76E-03 (98%)**	1.67E-06 (0%)	3.89E-05 (2%)	1.80E-03
Terrestrial ecotoxicity (kg DCB eq)	2.38E-04 (0%)	6.08E-04 (0%)	**1.48E-01 (96%)**	7.24E-04 (0%)	4.59E-03 (3%)	1.55E-01
Human ecotoxicity (kg DCB eq)	6.46E-06 (0%)	1.65E-05 (1%)	**2.19E-03 (94%)**	1.96E-05 (1%)	8.78E-05 (4%)	2.32E-03

The impact contributions from the construction and operation stage are combined in Table 3-37 so that the burdens can be traced to the processes causing them. As seen in Table 3-36 the largest contributions to the overall profile come from the operations stage. The screw pumps have the highest contribution since they are the largest electricity users.

Secondary Treatment Plant – Overall

From the individual stages an overall profile was constructed. This includes the construction, operations and decommissioning stages. Table 3-38 combines the contributions from the construction and operations stage. One can therefore see that the electricity used by the activated sludge unit is almost entirely responsible for all the environmental burdens associated with the secondary treatment plant.

Table 3-38: Overall environmental profile of the secondary treatment plant, showing the contributions from the construction, operation and decommissioning stages. The contribution from each stage is shown in parenthesis.

Impact category				
	Construction	Operation	Decommissioning	Total
Global Warming (kg CO2 eq)	3.34E-03 (1%)	**2.97E-01 (99%)**	1.20E-04 (0%)	3.01E-01
Ozone depletion (kg R11 eq)	1.24E-10 (2%)	**5.62E-09 (98%)**	0.00E+00 (0%)	5.74E-09
Acidification (kg SO2 eq)	2.04E-05 (1%)	**1.70E-03 (99%)**	1.02E-06 (0%)	1.72E-03
Eutrophication (kg Phosphate eq)	2.14E-06 (2%)	**1.09E-04 (98%)**	1.65E-07 (0%)	1.11E-04
Photo-oxidant (kg ethene eq)	7.35E-07 (3%)	**2.11E-05 (96%)**	2.08E-07 (1%)	2.21E-05
Aquatic ecotoxicity (kg DCB eq)	2.07E-05 (0%)	**4.75E-03 (100%)**	3.03E-08 (0%)	4.77E-03
Terrestrial ecotoxicity (kg DCB eq)	8.97E-03 (2%)	**4.00E-01 (98%)**	2.49E-05 (0%)	4.09E-01
Human ecotoxicity (kg DCB eq)	2.43E-04 (4%)	**5.90E-03 (96%)**	5.04E-07 (0%)	6.15E-03

Again as with the results from the primary treatment the operations stage dominates the environmental profile of the secondary treatment plant, as can be seen in the above table.

Table 3-39 shows the break down of where the impacts to the secondary treatment process are from. As expected due to the large power consumption of the activated sludge process, it is responsible for almost the entire environmental burden of the subsystem.

Table 3-39: Environmental burdens of each unit operation in the secondary treatment plant. Percentage contributions to the total environmental burden are shown in parenthesis.

Impact category	Activated sludge	Clarifiers	Total
Global Warming (kg CO2 eq)	**2.99E-01 (98%)**	5.64E-03 (2%)	3.05E-01
Ozone depletion (kg R11 eq)	**5.70E-09 (98%)**	1.29E-10 (2%)	5.82E-09
Acidification (kg SO2 eq)	**1.71E-03 (98%)**	3.27E-05 (2%)	1.74E-03
Eutrophication (kg Phosphate eq)	**1.10E-04 (98%)**	2.40E-06 (2%)	1.12E-04
Photo-oxidant (kg ethene eq)	**2.16E-05 (97%)**	5.84E-07 (3%)	2.22E-05
Aquatic ecotoxicity (kg DCB eq)	**4.76E-03 (98%)**	7.79E-05 (2%)	4.84E-03
Terrestrial ecotoxicity (kg DCB eq)	**4.05E-01 (98%)**	9.24E-03 (2%)	4.14E-01
Human ecotoxicity (kg DCB eq)	**6.05E-03 (97%)**	1.77E-04 (3%)	6.23E-03

3.4.2.5. Durban Water Recycling

Table 3-40 shows the overall burdens associated with the construction, operation and decommissioning stages of the recycling sub-system.

Table 3-40: Overall environmental profile of the tertiary treatment plant, showing the contributions from the construction, operation and decommissioning stages. The percentage contribution from each stage is shown on parenthesis.

Impact category	Construction	Operation	Decommissioning	Total
Global Warming (kg CO2 eq)	6.55E-03 (6%)	**9.42E-02 (93%)**	2.36E-04 (1%)	1.01E-01
Ozone depletion (kg R11 eq)	2.43E-10 (8%)	**2.95E-09 (92%)**	0.00E+00 (0%)	3.19E-09
Acidification (kg SO2 eq)	4.00E-05 (7%)	**5.26E-04 (93%)**	2.02E-06 (0%)	5.68E-04
Eutrophication (kg Phosphate eq)	4.19E-06 (12%)	**3.05E-05 (87%)**	3.26E-07 (1%)	3.51E-05
Photo-oxidant (kg ethene eq)	1.44E-06 (14%)	**8.63E-06 (82%)**	4.10E-07 (4%)	1.05E-05
Aquatic ecotoxicity (kg DCB eq)	4.05E-05 (4%)	**9.64E-04 (96%)**	5.97E-08 (0%)	1.00E-03
Terrestrial ecotoxicity (kg DCB eq)	1.76E-02 (14%)	**1.07E-01 (86%)**	4.92E-05 (0%)	1.25E-01
Human ecotoxicity (kg DCB eq)	4.77E-04 (27%)	**1.30E-03 (73%)**	9.93E-07 (0%)	1.77E-03

The relative contributions from the construction stage are higher for the tertiary treatment plant because the absolute inputs to the operations stage are very much lower than the other sub-systems. More than 95% of the contribution to the toxicity categories for the construction stage comes from the steel used in the manufacture of the pumps. Due to the larger number of pumps employed in the tertiary treatment process compared to the other two plants, the contribution from the construction phase for the ecotoxicity categories is higher.

The impact contributions from the construction and operation stage are combined in Table 3-41 so that the burdens can be traced to the processes causing them.

Table 3-41: Environmental burdens of each unit operation in the tertiary treatment plant. Percentage contributions to the total environmental burden are shown in parenthesis.

Impact category	Settlers	Dual Media	Ozonators	GAC	Chlorinators	Total
Global Warming (kg CO2 eq)	3.85E-02 (38%)	1.82E-03 (2%)	4.63E-02 (46%)	2.54E-03 (3%)	1.14E-02 (11%)	1.01E-01
Ozone depletion (kg R11 eq)	2.11E-09 (66%)	5.40E-11 (2%)	8.86E-10 (28%)	7.75E-11 (2%)	6.31E-11 (2%)	3.19E-09
Acidification (kg SO2 eq)	1.28E-04 (23%)	1.07E-05 (2%)	2.64E-04 (47%)	1.52E-05 (3%)	1.47E-04 (26%)	5.65E-04
Eutrophication (kg Phosphate eq)	6.92E-06 (20%)	9.08E-07 (3%)	1.71E-05 (49%)	1.38E-06 (4%)	8.38E-06 (24%)	3.47E-05
Photo-oxidant (kg ethene eq)	5.39E-06 (51%)	2.72E-07 (3%)	3.37E-06 (32%)	4.25E-07 (4%)	1.11E-06 (10%)	1.06E-05
Aquatic ecotoxicity (kg DCB eq)	2.12E-04 (21%)	2.01E-05 (2%)	7.34E-04 (73%)	2.45E-05 (2%)	1.06E-05 (1%)	1.00E-03
Terrestrial ecotoxicity (kg DCB eq)	4.75E-02 (38%)	3.70E-03 (3%)	6.30E-02 (51%)	5.62E-03 (5%)	4.60E-03 (4%)	1.24E-01
Human ecotoxicity (kg DCB eq)	3.30E-03 (71%)	8.44E-05 (2%)	9.49E-04 (21%)	1.38E-04 (3%)	1.55E-04 (3%)	4.63E-03

Table 3-41 shows that a large proportion of the impacts can be attributed to the ozonation unit. This is due to the fact that this unit is the largest electricity consumer of the tertiary plant. The impacts associated with the lamellae settlers come mainly from the chemicals used in the treatment process since the addition of the chemicals were modelled as being part of the settler unit. Toxicity tests were carried out to determine the effect of sending the sludges from the settlers to the deep sea outfall. Appendix 2 considers the details of the toxicity tests.

3.4.2.6. Durban Southern Deep Sea Outfall

An important distinction between different LCA studies of wastewater systems is whether sludge is regarded as a resource or a waste product. A few studies (Neumayr et al, 1997 and Sonneson et al, 1997) consider the recycling of the nutrients from sludge but most others consider sludge a waste problem. Some studies even show that the effluent from the outfall has a beneficial effect on the marine environment. A worst case was assumed and thus the effluent discharged was treated as a waste stream.

As stated previously the impacts from the sea outfall all fall within the aquatic ecotoxicity category. It must be remembered that this is the ecotoxicity of the effluent measured at the inlet to the outfall. The outfall is designed to high effluent maximum mixing and dilution specifications. Thus by the time the effluent reaches the sea surface the effluent is diluted a minimum of 250 fold. However it is important to know the maximum toxicity, as this is the measurement that will effect organisms close to the pipeline discharge point.

3.4.3. Improvement Analysis

Having established that the dam was responsible for only a small portion of the total environmental burden, the units causing a large burden were investigated and potential improvements were suggested to see if the environmental load could be reduced.

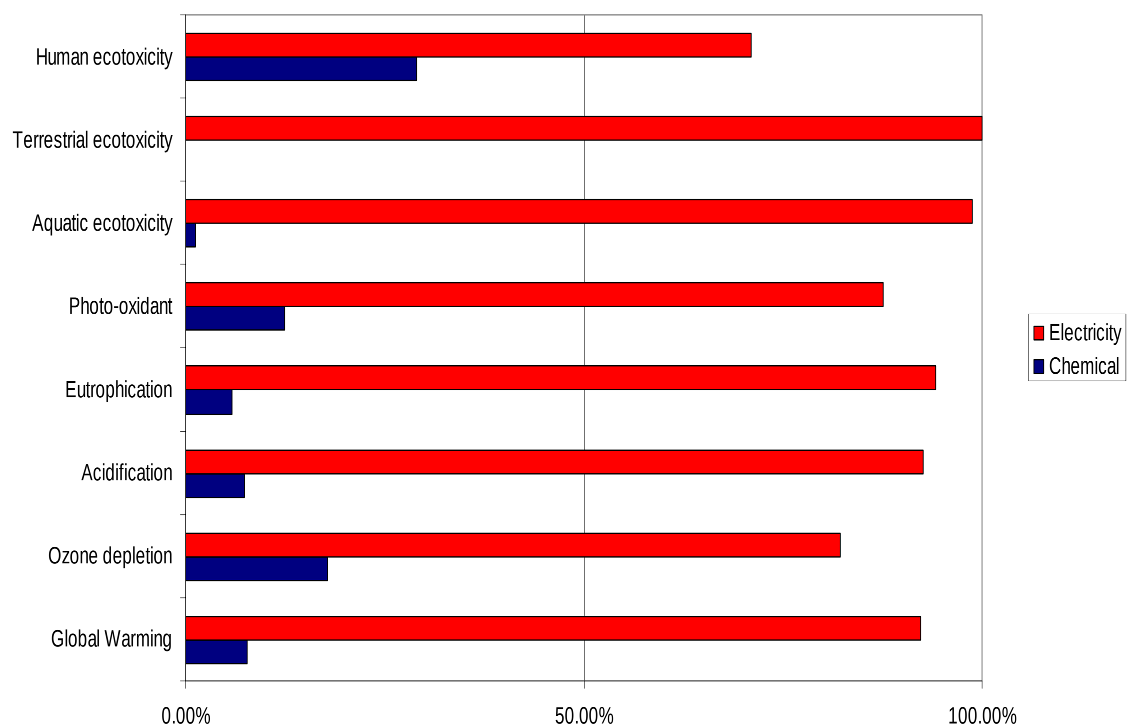

Figure 3-5: Environmental burden of the contribution to the operations stage from chemical and electrical inputs to the system.

From the graph it is clear that the environmental burden of the system is largely due to the electrical input. The environmental burden of electricity production in South Africa will be discussed in Chapter 5. The process units that were high users of electricity were then targeted for improvement measures.

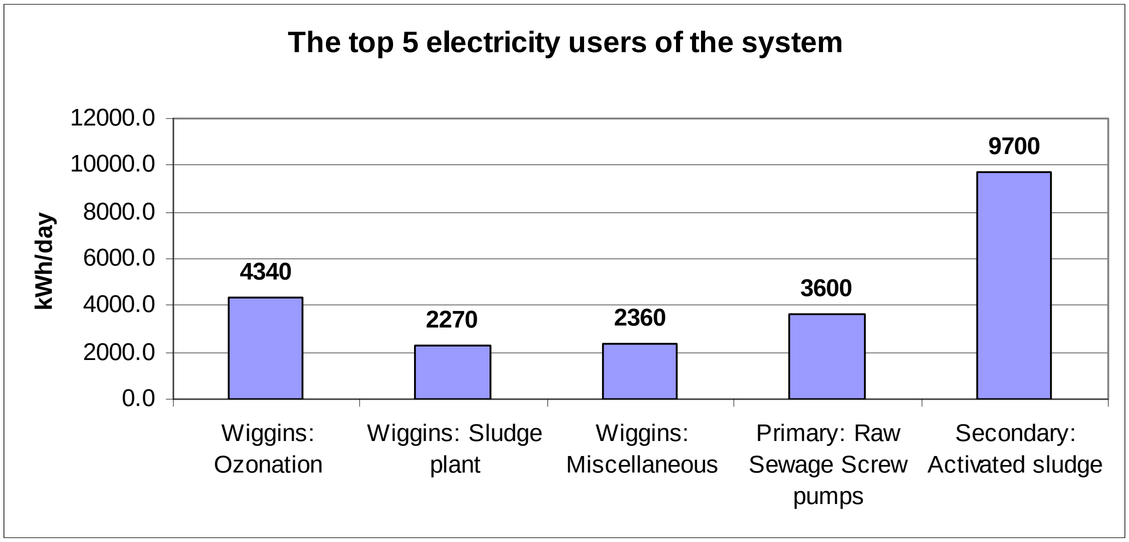

Figure 3-6: Graph of the top electricity intensive processes for the operations phase of the system.

The graph shows that the highest users of electricity are the collection and distribution of water, the activated sludge unit and the units associated with the production and destruction of ozone. These units were examined in greater detail in order to see whether their consumption of electricity could be decreased.

3.4.3.1. Ozonation

The ozonation unit is comprised of two sections, the ozone generator, which uses electricity to generate ozone from oxygen and the thermal destruction unit, which destroys the excess ozone by heating the gases to 300 ^{o}C. Of the 4 314.4 kWh/d used by the ozonation unit, 3 140.5 kWh/d (72.38%) is used for the thermal destruction unit.

It was found that by limiting the air flow to the thermal destructor, thus increasing the concentration of ozone in the gas entering the unit and decreasing the total volumetric flow the electricity consumption of the unit was decreased. A series of preliminary tests were run on the ozonators to determine the effect of reducing the gas flow to the thermal destruction unit by partially closing the vacuum breaker on top of the contactors (Pillay, 2002). Also better control of the ozone dosing would reduce the need to have ozone destruction.

Based on trials that were conducted on this unit it was found that a 70% electricity reduction could be achieved. This would translate to a similar environmental saving. This is only a particular case study and this does not mean that similar savings could be achieved on all ozonation units.

3.4.3.2. Activated Sludge

The impacts from the activated sludge units can be attributed to the large amount of electricity expended by the aerators in transferring air from the atmosphere into the liquid. Surface aerators are used at the Southern Wastewater Treatment Works. The reason for this is due to the fact that many aeration processes fail to achieve an optimum level of energy consumption (Houk and Boon, 1981). Table 3-42 shows the different oxygen transfer efficiencies for different aeration methods.

Table 3-42: Oxygen transfer efficiencies of different aeration methods (Gray, 1990)

Aeration method	Energy efficiency ($kg\ O_2/kWh$)
Coarse bubble diffusers	0.8-1.2
Fine bubble diffusers	2.0-2.5
Vertical shaft aerators	1.5-2.3

Two possible ways of reducing the electrical load were considered. The first is to use a fine bubble diffused aeration system in conjunction with the current surface aerators as this has a high oxygen transfer efficiency.

Provisions have already been made for periods of high demand and oxygen diffusers are in place. Problems associated with this system are the high cost of pumping (electrical and hence environmental) pressurised air and fouling of the diffuser network.

A second way of reducing the electrical load is to decrease the oxygen demand of the system. This can be achieved by optimising parameters such as sludge age, wastage rate, aeration levels and recycle rate. A computer model was set up using the WEST (Worldwide Engine for Simulation, Training and Automation) software package to investigate these parameters.

Figure 3-7 presents the preliminary results from this model. It was shown that a decrease in the dissolved oxygen set point from 2.0 mg/L (O_2 set point 2) to 1.5mg/L (O_2 set point 1) resulted in a negligible change in the COD reduction (from COD out 2 to COD out 1). This reduction in the oxygen required by the process translates to a large electrical saving by the aerators. It must be noted that these are preliminary results and need to be investigated further to see whether this change can be implemented on the plant. One of the factors that need to be considered is that the aerators have a dual function. They transfer oxygen to the sludge as well as keeping it well mixed. Thus it needs to be investigated how reducing the air input to the tanks will affect the mixing of the tanks.

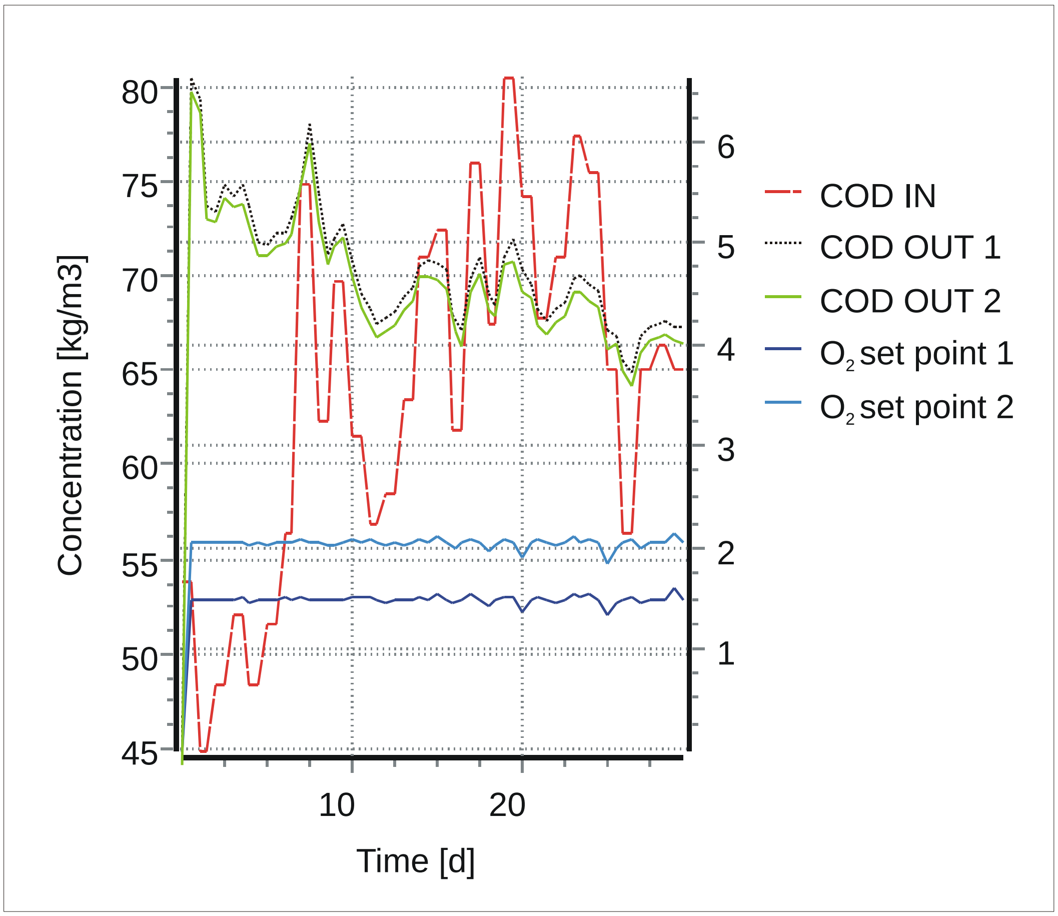

Figure 3-7: Outputs from WEST model, showing the change in COD reduction after changing the dissolved oxygen set point.

Another option that requires further investigation is the pre-treatment of the entering effluent. Mels et al. (1999) showed that by introducing a pre-treatment step the energy requirements of the activated sludge could be reduced. Two pre-treatment options were considered. The first (Scenario A) used the addition of coagulant and flocculent followed by a settling stage. The second (Scenario B) used the addition of coagulant and flocculent followed by a flotation stage.

The reference system had a similar same set up as the secondary treatment plant in this study,although the entering effluent had a lower BOD. It was found that the electricity usage could be reduced from 3 00 MWh/year to 50 MWh/year for Scenario A and to 30 MWh/year for Scenario B. For a South African treatment system this option is not used as the cost of chemicals outweighs the electrical savings. However the environmental improvements are potentially large.

3.4.4. The Electricity Index as an Environmental Performance Indicator

From the previous sections it was concluded that electricity plays an important role for the environmental performance of water systems. Electricity is the highest contributor for all of the environmental LCA scores for the production and distribution of potable water as well as for the collection and treatment of wastewater. Therefore, this section proposes the use of an electricity index as a measure of environmental performance for urban water systems in South Africa. The amount of energy expressed as kWh/kL of water (potable or wastewater) is enough to simplistically judge the overall environmental performance of existing water systems. It is also a relatively easy index to use from the point of view of the technical staff involved in operating water plants and pumping stations and which usually are not familiar with global warming and CO_2 equivalents. The use of an electricity index would be a good measure, as long as the underlying data (i.e. electricity consumption) can be measured reliably and assigned to different operations or processes. For some municipalities this is not always the case. In this study it took a lot of time and effort to get satisfactory electricity data. The other instance where this index is inappropriate is when the topography of a municipality allows for water systems in which pumping is not required.

The close relationship between the electricity consumption per kiloliter of water/wastewater and the environmental LCA scores is shown in Figure 3-8. Due to the differences in the magnitude of the scores a logarithmic representation was chosen. As this figure shows, the shapes of all curves follow the shape of the electricity curve and there are no major discrepancies.

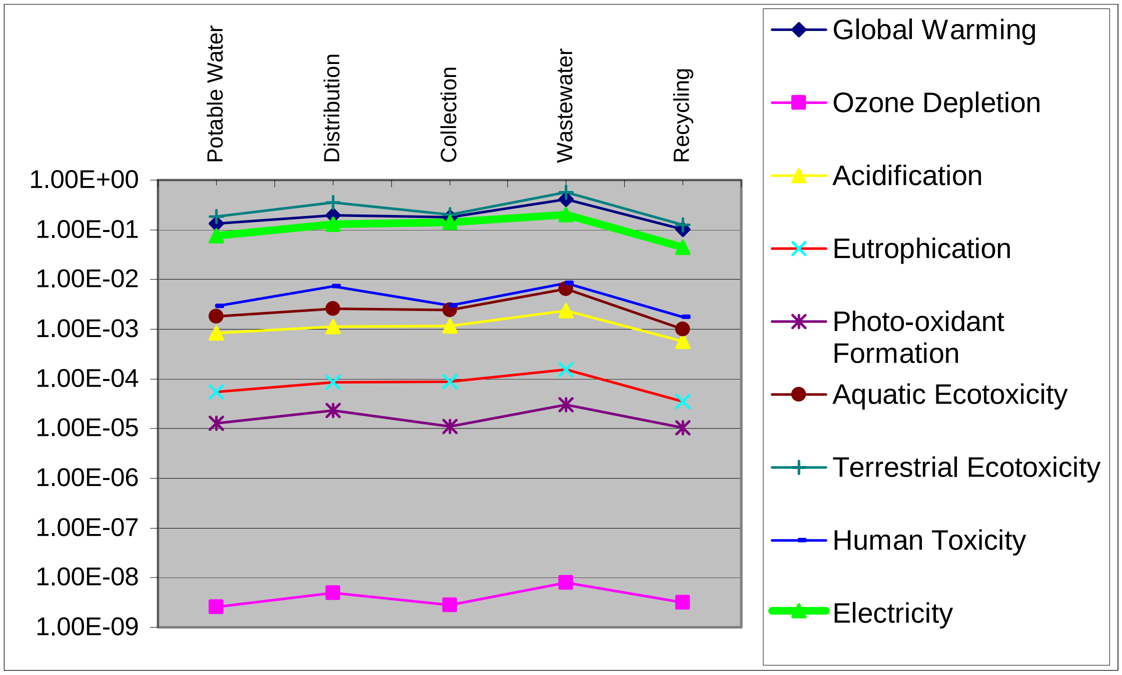

Figure 3-8: Logarithmic representation of LCA scores in relation to electricity

This figure also indicates that a decrease in the electricity consumption of a unit would result in an improvement in environmental performance for all the studied impact categories. Thus no burden shifting across categories occurs. Detailed data on electricity production in South Africa is presented in Chapter 5.

3.5. Discussion

The general assumptions that apply to the entire study and their validity are now discussed;

1. *The design and conceptualisation stage has little direct burden;* This was shown to be true by Rebitzer and Hunkeler in 2002 in their paper on simplifying life cycle assessment. This study has also shown clearly that the environmental impacts of this system are proportional to the energy input. Thus, since the energy input to the design stage is relatively small it is valid to assume that it has little impact but the consequences of poor or good design are large.

2. *The entire system is operating under normal operating conditions;* During the time period of study (1 year of operating data) very few incidents of abnormal operation were recorded. These were usually associated with the recycling and secondary treatment plants as the processes in these sub-systems were still being modified or a failure in one

of the control mechanisms. LCA is not considered a suitable tool to be used for evaluating the environmental impact of an abnormal operating conditions. Risk assessment is better suited to this.

3. *Streamlined LCA was used for some of the sub-systems*. From the detailed LCAs of the waterworks, primary, secondary and tertiary systems it was clearly shown that the construction and decommissioning phase had a small contribution to the overall impact of each sub-system. Thus it was decided that for the dam and sea outfall these stages would not be studied in detail, however since these systems are different in nature to the other sub-systems, simple order of magnitude calculations were carried out (Appendix 1) which vindicated the decision to leave the construction and decommissioning stage out. In fact it is now common practice to leave out these stages for energy intensive processes.

   A study by Beavis (2003) at the Sydney Water Inland Wastewater Treatment plant comparing anaerobic digestion to aerobic digestion showed similar results to this study. The differences in his study where that; the entering sewage is treated by a dissolved air flotation unit before entering the activated sludge unit and that only the operations stage was considered. Also not all the impact categories that where used for this study were considered, however it is worthwhile presenting his results to show the similarities. This comparison is presented in Table 3-43

Table 3-43: Table showing the results of this study compared to those of Beavis (2003) showing the results of the impact analysis for the operations stage of the secondary treatment process.

Impact category		
	Beavis	Calculated
Global Warming (kg CO2 eq)	2.82E-01	2.97E-01
Acidification (kg SO2 eq)	1.60E-03	1.70E-03
Photo-oxidant (kg ethene eq)	1.30E-04	2.11E-05
Aquatic ecotoxicity (kg DCB eq)	7.70E-03	4.75E-03
Terrestrial ecotoxicity (kg DCB eq)	1.08E00	4.00E-01
Human ecotoxicity (kg DCB eq)	6.60E-03	5.90E-03

Hwang and Hanaki (2000) showed similar results in their study on the generation of carbon dioxide in sewage sludge treatment. The process units that were studied included, gravity settling and air flotation. For all their studied units it was shown that the operations phase was the dominant contributor to carbon dioxide emissions and that this was mainly due to the electricity used during the operation.

In a study on the application of the LCA methodology to water management from the pumping station to the wastewater treatment plant Rihon (2002) showed a similar finding in that the most significant impacts in his study could be attributed to the secondary and sludge treatment stages of the studied system. The secondary treatment stage in his system was a conventional one, similar to the one in this study. Again the environmental impacts were largely attributed to the electricity use of the plant.

The results of Zhang and Wilson (2000) in their study on the life cycle assessment of a sewage treatment plant in South East-Asia differed to some degree from the results of this study. Using a system similar to the primary and secondary treatment sub-systems under study here, they found that the operations phase was the most energy consuming part in the whole life-time. Energy consumed in this phase (both direct and indirect) accounted for 67.5% of the total energy consumption. This proportion of electricity used in the operations stage not only differs from the results of this study but also the results of Emmerson (1995) and Owen (1982) whose results closely match this study. This is probably due the following reasons as suggested by the authors;

i. A high ambient temperature (28 ^{o}C) allowing for a shorter residence time.

ii. The ‘periodic air application’ technique is engaged in the aeration process to solve the problem of bacterial forming. The aeration units are operated with periodic cycles, each comprising aeration and air-termination stages, which can save part of the energy required for aeration because the air is transferred intermittently instead of continuously as in this study.

iii. Good administration helps to reduce operational consumption. The sewage plant they studied operated at a much lower energy consuming level compared to its original design estimates. In South Africa where electricity is relatively cheap greater emphasis is placed on optimising chemicals use in the treatment processes.

4. *Only primary inputs of energy and materials are considered;* Hunt (1991) demonstrated that the impacts of secondary inputs were small (less than 5% of the overall impact) and

that it did not improve the results of the LCA greatly by including them. This is, however, dependent on the materials used for construction. In fact the impacts from electricity use are so great that in their LCA study on the environmental impact of wastewater treatment Lundin et al. (2000) concentrated on just the electrical inputs to the secondary and tertiary treatment processes. The study used a similar system to this study however the one major difference was that as the sludge was used as a fertiliser it was considered a resource rather than a waste product as in this study.

5. *Secondary data was used for the background systems;* Although energy plays an important role in the environmental impacts of the system it would have been time consuming to conduct an LCA of the South African electricity mix and was not the main objective of this study. Instead a commercial coal based electricity mix was used based on European conditions. This choice will have a relative scaling effect and not change the rank order. Chapter 4 considers the effect of this choice.

6. *For the life cycle inventories, any missing data was calculated using a worst case scenario;* This assumption applied mainly to the dam where very little monitoring of the emissions takes place. Here the decision was taken to err on the side of caution by using a Brazilian model to calculate the dam emissions rather than one from the Northern hemisphere although this model would result in a higher level of calculated emissions.

7. *The effects of the greenhouse gases are modelled over a 100 year period.* The global warming potential of different greenhouse gases with reference to carbon dioxide vary over the time period considered. For example, methane has a global warming potential of 62 times that of carbon dioxide over a twenty year period but this drops to 23 times over a hundred year period. It is now common practice to report the global warming effect over a hundred year period. The largest two greenhouse gas emissions in this study are methane and carbon dioxide. Methane has an atmospheric lifetime of approximately 12 years while carbon dioxide can remain in the atmosphere for a much longer period and have a global warming effect for hundreds of years (IPCC, 2001). Thus by choosing too short a time period the effects of the methane would be exaggerated and hence a hundred year period was chosen.

While being a valuable environmental tool LCA has some limitations. Van den Berg et al, 1995 presented these and those that are relevant to this study and require highlighting are;

- LCA cannot judge decisions related to the location of a building or activity. In that case Environmental Impact Assessment is more appropriate. This is particularly true for the construction of the dam and the marine discharge pipeline, where a large portion of the environmental impacts are related to the location and construction and do not fall into any of the studied LCA categories.
- LCA does not provide answers for risk related questions in which case a hazard or risk assessment should be used. This is relevant to the processes which use toxic chemicals. In particular the ozonation processes and the disposal of the sludge to sea. LCA does not take into account a system failure and the event of a hazardous substance release.

What this LCA does do is identify, quantify, interpret and evaluate the environmental impacts of the studied water system. The LCA also identifies the environmentally most dominant stage in the life cycle of each system and sub-system and hence (as will be shown in Chapter 6) indicates the main routes towards environmental improvements. It does this in a systematic and scientific manner.

Based on the impact assessment results, the major contributors at each stage were identified. Most environmental impacts result from the operation stage. This is in line with many other LCA studies on water treatment processes (Emmerson et al., 1995, Meijers et al., 1998, Grabski et al., 1996) where it turned out that the use stage tends to be the most influential due to the continuous use of energy and material. The results have also shown that the use of an electricity index is a reliable indicator of environmental performance for water and wastewater treatment processes.

The overall environmental profile of the system will be presented in Chapter 6 which considers various scenarios and uses the described system as a base case.

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Chapter 4 : Social Impact Analysis

By definition (Section 3.1), LCA only considers environmental issues. In reality, there are also other issues, e.g. social, economical, political and technical, that cannot be ignored in any decision (Miettinen, 1997). Attempts have been made to include social impact categories into the LCA framework but so far there is no standard method of doing so. This is probably due to the wide range of social impacts and the fact that they are usually site sensitive. For example one of the social impact categories that have been mooted is that of job creation. This category is highly dependent on the type of economy where the LCA study is taking place. Developing countries tend to use much more labour intensive processes as opposed to developed countries that prefer mechanisation and automation.

An important reason to consider social impacts is their linkage to environmental impacts, UNEP (1996) cites two examples;

- there is often a direct link between social and subsequent biophysical impacts. For example, a project in a rural area can result in the in migration of a large labour force, often with families, into an area with a low population density. This increase in population can result in adverse biophysical impacts, unless the required supporting social and physical infrastructure is provided at the correct time and place.
- direct environmental impacts can cause social changes which, in turn, can result in significant environmental impacts. For example, clearing of vegetation from a riverbank in Kenya to assist construction and operation of a dam eliminated local tsetse fly habitats. This meant that local people and their livestock could move into the area and settle in new villages. The people exploited the newly available resources in an unsuitable way, by significantly reducing wildlife populations and the numbers of trees and other wood species which were used as fuel wood. A purely environmental assessment might have missed this consequence because the social aspects of actions associated with dam construction would not have been investigated.

For the purposes of this study one must understand the different time periods and the different social conditions that prevailed. Inanda Dam was constructed in 1988 and the recycling plant 15 years later. In this interval the entire social structure in South Africa changed and hence the social norms. South Africa held its first democratic elections in 1994, emerging from a history of colonial domination and racial segregation, which reached its culmination in the apartheid policies of the Nationalist government (1948-1994). Where it was once the practice to relocate people without compensation and without an environmental impact study, the early 1990s has seen the introduction of stringent legislation which requires detailed environmental impact studies that include social impact assessments.

This chapter opens with Section 4.1 where the historical background of social impact analysis is discussed. Here the different types of social analyses are presented and the link between social impact analysis and LCA is examined. Section 4.2 continues with the theory and methodology chosen for this particular study. Here mention must be made that the aim of this study is not to provide an in-depth social analysis but rather to present some of the social impacts so that a more complete picture can be created when examining the system and each sub-system by considering both environmental and social impacts. The results are presented in Section 4.3 and the chapter concludes with a discussion of these results in Section 4.4.

4.1. Historical back ground

Social impacts are the impacts of a project, plan, programme or policy on people. Social impact assessment is an integral part an environmental assessment report and is mandatory in some countries e.g. the United States under the National Environmental Protection Act (NEPA), 1969. The Inter-organisational Committee on Guidelines and Principals for Social Assessment, 1994 defined social impacts as;

The consequences to human populations of any public or private actions – that alter the ways in which people live, work, play, relate to one another, organize to meet their needs and generally cope as members of society.

Consideration of social impacts contributes to better decision making that balances social, economic, and environmental objectives. Many different methods have been developed to analyse impacts and they can be grouped into three broad categories;

- Economic based methods which seek to monetarise social costs and benefits;
- Indicator based methods which monitor changes over time in particular areas of social concern (e.g. indicators on unemployment, crime and homelessness); and

• Judgment based methods which assess options against various weighted criteria (e.g. planning balance sheet, goals achievement matrix).

The Human Development Index (HDI) is an indicator method which is used by the United Nations. Based on 1994 data, the United Nations Development Program (UNDP) listed South Africa as 90 on the Human Development Index (Medium Human Development). Based on those figures SA's HDI value was given as 0.716, close to those of Peru, Oman and the Dominican Republic (UNDP, 1999). The most recent UNDP listings however place SA as number 120 out of 174 countries. This fall is attributable mainly to the AIDS epidemic and the resultant decrease in life expectancy and increase in the child mortality rate (Schreiner, 2000).

Table 4-1 shows the broad categories of social impacts used by different researchers.

Table 4-1: Types of Social Impacts (taken from Glasson, 1995)

- Direct economic including labour force, local/ non local employment, income and patterns of employment;
- Demographic including changes in population size (temporary and permanent), displacement and relocation, changes in population makeup and settlement patterns;
- Services/ institutional including housing (tenure, prices, homeless issues), education provision, health and welfare services, policing and justice (crime), recreation and the demands on government and NGOs;
- Wider economic including income and employment multiplier, prices of local goods and services, local finances and taxation effects
- Cultural including impacts on traditional patterns of life and work, family structure and authority, religion and tribal factors, archaeological features, social networks and community cohesion;
- Gender including the implications of development actions on women's role in society, income generating opportunities, access to resources and employment opportunities

Other dimensions to social impacts include adverse and beneficial effects; reversible and irreversible; quantitative and qualitative and actual and perceived.

4.2. Methodology

For the purposes of this study it was decided to use a judgement based method to evaluate the impacts. The presence of value judgements in life-cycle impact assessment (LCIA) has been a constant source of controversy. However the present LCA methodology can be construed as containing value judgements. The example of the equivalency potential (see Section 3.1) for climate change, the global warming potential, demonstrates that any impact assessment method inevitably contains not only constitutive and contextual values, but also preference values

(Hertwich et al. 2000). In fact Hertwich felt strongly about the need to include value judgements in the LCA methodology as can be seen from his submission to the chair of the ISO committee on LCA standards;

…*Hertwich and Pease express concern that the 14042 document* (on LCI and LCA methodology) *imposes extreme constraints and limitations on LCA and LCIA, especially for the case of comparative assertions. They characterise the language used in the committee draft as being natural science biased ignoring insights from academic disciplines that address value questions...*

The social impacts for this study were evaluated using a life cycle assessment type methodology where all the inputs and outputs were considered and evaluated using a judgement method. Similarly when considering each process the LCA methodology used to evaluate the environmental impacts was used. Each unit was separated into a construction, operation and decommissioning phase and evaluated. One must remember the social analysis was included in order to create a holistic picture of the system and as stated by the World Bank, 1991 'Social analysis in environmental assessment is not expected to be a complete sociological study nor a cost-benefit analysis of the project'.

The Interorganisational Committee on Guidelines and Principles for Social Impact Assessments (1994) highlighted 3 crucial areas of any social impact assessment. They are;

i. It is more important to identify likely social impacts than to precisely quantify the more obvious social impacts.

ii. It is important to be on the 'conservative' side in reporting likely social impacts.

iii. The less reliable data there are on the effects of the projects or policy change, the more important it is to have social impact analysis work performed.

With regard to area (i) and (ii); firstly an attempt was made to include all the observed impacts and to quantify the important ones and secondly the 'conservative' approach was followed when quantifying these impacts. There are two types of social impact assessments, predictive and retrospective. This study presents observed impacts unlike the predictive case. Therefore, the last point in the above list is not relevant to this study. The best way to describe this analysis is 'a social impact assessment carried out using life cycle thinking'.

A broad indicator is used for each category. Indicators provide a summary of conditions, rather like body temperature and blood pressure are used to measure human health status. Indicators have been used for many years by economists to explain economic trends but have only recently been introduced to measure social impacts (Walmsley, 2001). Two impact categories, common to all process units, were identified for use as indicators for this study. These are *job creation* and *health and health risks*. No attempt is made to quantify the impacts in terms of a functional unit for the *health and health risks category* however the *job creation* category is measured using an indicator and then quantified in terms of the functional unit described in Chapter 3. Both the categories are inter-related as stated in the 2002 European Health report

...underlines the relation between socioeconomic factors and health. Poverty, in particular is recognized as the most important single determinant of ill health…

In a country like South Africa which has a high unemployment rate, job creation is critical in reducing poverty and thus raising the health level of the population. A World Bank study in 1999 showed the critical relationship between per capita Gross National Product (GNP) and the health of a population. Figure 4-1 shows these findings. In general, it is seen that among the countries below $5000 per capita GNP there is a very steep influence of economic growth. Thus job creation is considered a positive social impact with a multiplier effect.

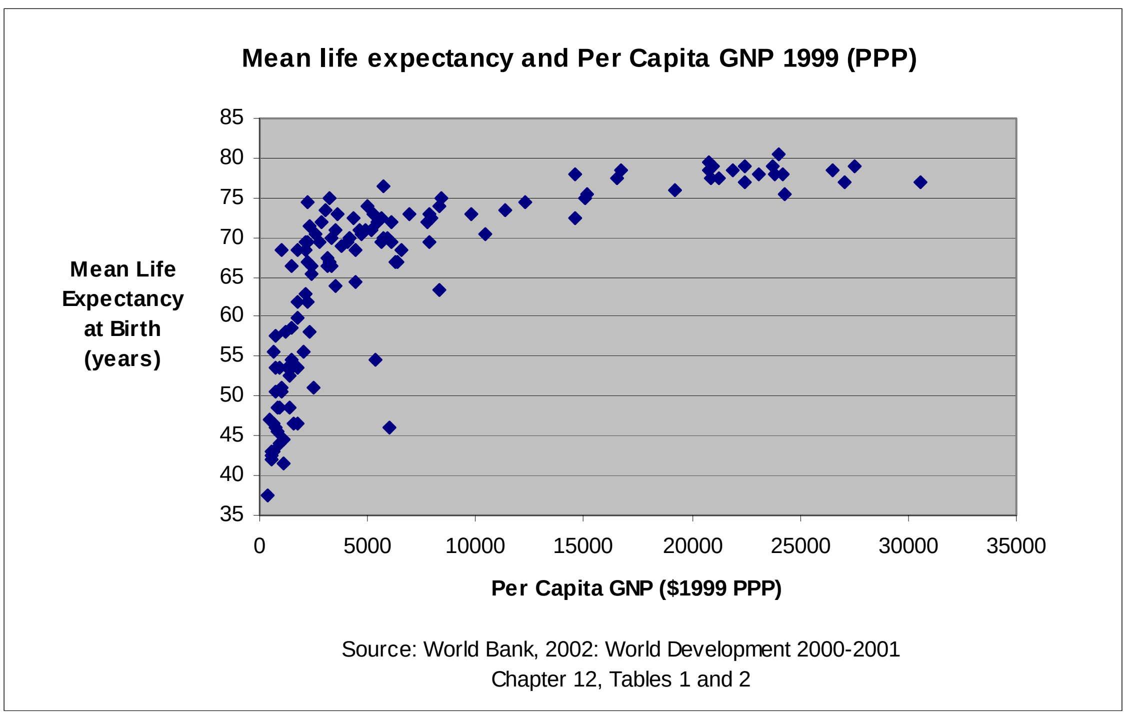

Figure 4-1: Mean life expectancy at birth in relation to per capita gross national product

As in the case of the environmental LCA, social impacts that do not fall into these two categories are still presented to create a holistic picture. The impact categories and their measure are defined as follows

Job Creation

South Africa is a developing country where the level of technology ranges from very high-tech industries to basic outdated technology. Problems concerning labour relations arose due to political imbalances, resulting in revenue losses by industry. Process, product and service optimisation to minimise waste generation is secondary to immediate bottom line improvements like the increase of sales and the reduction of labour and purchasing costs (Stinnes et al., 1996).

The impact category of job creation relates to the creation of direct and indirect jobs. In this study a *job unit* is defined as a job for one person for 25 years. This is in order to calculate the number of permanent jobs created. Thus for a short project like the construction of a dam which has a duration of between 5 to 10 years the number of people employed by the project are multiplied by the number of years worked on the project and divided by 25 in order to calculate the number of permanent jobs created by the project. Since it is difficult to get accurate figures for the number of people employed four broad bands were created to categorise the job creation category. Table 4-2 shows the indicator bands for the job creation category.

Table 4-2: Job creation category indicator bands

Band	Job Units
Small	0-50
Medium	50-100
Large	100-500
Very Large	500+

The job creation impact category is considered a beneficial social impact. One can make the generalisation that those policies or decisions that cause money to be spent will tend to have the highest job-creation effects; those that prevent money from being spent or somehow reduce spending will not measure up well on the job scorecard. When quantifying the job creation score in terms of the functional unit the median of each band was used and in the case of the very large band this was taken to be 1000 job units.

Health and Health Risks

Numerous vector borne diseases are associated with dam development in tropical and sub tropical areas. Bilharzia spread through snails breeding in still or slow moving water was a significant health problem that emerged from many early projects such as Kariba, Aswan and Akosombo. (Kariba dam in Hira, 1969. and Mungomba et al., 1993, Akosombo and Aswan dams in Jobin, 1999, p278, 298-300.) Most reservoir and irrigation projects in malaria endemic areas increase malaria transmission and disease (World Bank 1999b, p2)

Destruction of community food supply bases can lead to food shortages, resulting in hunger and malnutrition. Food shortages due to resettlement factors have been reported in Vietnam, China, Malaysia, Thailand and India. (China in Jing, op cit p10; Vietnam in Sluiter, op cit pVII; Malaysia in ADM, 1999a, p5, 2000; Thailand in Sretthachau et, 2000, WCD Regional Consultation Paper; India in Laxman, 1999, p208).

In recent years the high incidence of HIV/AIDS in construction and settlement areas is a growing concern. In the Lesotho Highlands Project Area, infection rates are far higher than surrounding areas. (Macoun et al, 2000). Communities are concerned about transmission from migrant workers arriving to work in the Maguga project in Swaziland. (WHO, op cit, p12).

Health is a primary need; it is also a primary indicator of levels of satisfaction of other basic human needs; finally it is an enabler of development. - (Norris, 2004)

Three indicator bands were created to evaluate this social impact category. They are described in Table 4-3;

Table 4-3: Health and Health Risks category indicators

Band	Definition
Low	Low incidence of injuries, project does not cause a great degree of pollution which affects human health
Medium	Medium incidence of injuries, project causes a moderate amount of pollution affecting human health
High	High incidence of life threatening injuries, project causes extensive pollution, affecting human health

As stated previously, the social indicators are calculated using a judgement based method therefore there is no quantification of the health risks. Some social methods use indicators such as effect on life expectancy, or child mortality however it is not practical to use those kinds of indicators for this study mainly because of the small size of the system.

It is worth mentioning a unit of measuring health impacts that is gaining popularity amongst LCA practitioners. The Disability Adjusted Life Years (DALY) is a single measure of health impacts that includes the effects of waterborne diseases and chemical impacts. It also includes years lived with a disability and years lost owing to premature death in a common metric (Havelaar et al., 2000). It can be used to represent the loss of healthy life years in the community owing to any hazard.

The health and health risks impact category is considered an adverse impact.

4.3. Results

The results of the social impact analysis are now presented. As with the life cycle assessment in Chapter 3 this section is divided into the same sub-systems and the results presented individually.

4.3.1. Inanda Dam

The social impacts relating to dams and in particular Inanda Dam are a controversial issue. They include among them the impacts associated with the forced removal of an entire community. The social effects of large scale infrastructural developments are not unique to South Africa; however one must bear in mind the historical context of the dam development. In both developed and developing country contexts, developments for the public good have undesirable consequences for the local people living in the vicinity of the particular development (Sørenson, 1984). The planning and construction of Inanda Dam took place during the 1980s when South Africa was still under the apartheid system of government. Therefore, in the South African context this kind of development was a political issue since the people affected were mainly black. During the 1980s black people had no political leverage with the national departments, that made and applied the nature and siting of development projects, and generally did not benefit from the projects which were developed on the land on which they lived (Willard, 1984).

The government claimed that Inanda Dam project was to be executed with minimal effect on the social and physical environment (Government Gazette, 1987). In the case of Inanda Dam the local black population, to be affected by the dam development, were not consulted although it was reported that as far back as 1978, the local chiefs were visited by planners from the national department and informed of the future dam (Platsky, 1985). No evidence exists of any negotiations between local or KwaZulu leaders regarding the building of the dam, although opposition to the project was recognised (White paper, 1981).

Four tribes were affected by the dam development. Information regarding the number of people affected range widely, from the newspaper reports of 8 000 to 12 000 (Daily News, 1987) and 5 500 (Natal Mercury, 1983); survey reports of 12 000 to 14 000 (Tollman, 1981) and 25 000 (Willard,1984) and the official estimate of 3 500 (White Paper, 1981). As early as 1981 voluntary relocation commenced in anticipation of forced removal at some later date. The tribes people moved to an area in the township of Inanda informal settlement called Lindelani, '*the place of waiting*'. Here they were required to pay landlords for sites to build their own shacks. (Scott, 1989).

The exact method of calculating compensation is known only to the Department of Development Aid and under the Co-operation and Development Act of 1982, secrecy has been maintained about the rates of compensation and the numbers of relocatees (Willard, 1984). Furthermore, compensation was non-negotiable and took the form of a cash payment. R3.5 million was set aside by the central government to purchase alternate land and pay compensation costs (White Paper, 1985). In all categories of relocation, compensation was a particularly controversial issue and few people were satisfied with the money received (Platsky, 1985). It must be noted that the compensation money was not paid directly to the affected people. Instead this money was paid to the tribal chiefs. In many cases the bulk of the money remained with the chiefs and very little was re-distributed.

A survey undertaken by the Surplus People's Project (SPP) in 1980/81 (SPP, 1983) revealed that the living conditions were very poor in Inanda. Residents were given a site, a tent and a days' ration and were expected to replace these with self built houses.

Table 4-4 outlines the main effects of relocation on the affected community.

Table 4-4: Effects of relocation on the communities inhabiting the Inanda Dam area

- Inadequate compensation to replace traditional homesteads
- Deprives relocatees of farming land which they depend on for subsistence
- Lack of subsistence farming and the high cost of living this results in a less nutritious diet and malnutrition
- Relocatees experience a new set of social norms which can be stressful and disorientating
- Disruption of social networks undermines the political and social unity of the group

In 2000 the World Commission on Dams (WCD, 2000) found that;

…those who were resettled have rarely had their livelihoods restored, as resettlement programmes have focused on physical relocation rather than the economic and social development of the displaced.

This is a common problem throughout the world and the WCD statement highlighted this lack of capacity to cope with displacement. In other countries and perhaps in future dam development projects in South Africa the WCD stated;

…the poor, other vulnerable groups and future generations are likely to bear a disproportionate share of the social and environmental costs of large dam projects without gaining a commensurate share of the economic benefits.

Even though it can be argued that the Inanda Dam is a necessity for the future survival of people in the eThekwini Municipality and that the relocation of relatively few people is for the public good, the manner in which the removals have occurred classifies them as part of the apartheid policy (Scott, 1989).

4.3.1.1. Job Creation

When evaluating the impacts, as with the LCIA the impacts where evaluated separately for the construction, operation and decommissioning phase.

Construction

During the construction period, dam projects require a large number of unskilled workers and a smaller but significant amounts of skilled labour. New jobs are therefore created for both skilled and unskilled workers during the construction phase. No studies have been performed on the labour impacts of the Inanda Dam project therefore, in order to estimate the number of jobs created studies of other dam projects in South Africa and other developing countries were used. In the Orange River Development Project, the loss of 4 000 jobs was avoided and effectively some 16 000 seasonal jobs were created in downstream areas by the dams and associated irrigation development. In total some 40 000 jobs were created or saved (regular and seasonal combined) (WCD, 2000). Comparisons with construction of dams in other developing countries reveal a similar figure. The Kariba and Grand Coulee dams employed between 10 000 and 15 000 workers each. During the peak construction period a labour force of about 15 000 people were employed at Tarbela Dam (Asianics, 2000). These projects are much larger than the Inanda

Dam project as they included hydroelectric power generation and irrigation schemes. For a comparatively small development like that at Inanda it is estimated that at peak, between 5 000 and 10 000 workers were employed.

Using the indicators defined earlier the job creation score for Inanda Dam falls into the **Very Large** category as more than 500 *job units* were created. This translates to 7.14E-05 job creation units/kL.

Operation

Another function of the dam is as a tourist attraction. The dam is a popular site for bass fishermen and canoeists. Chalets and camping sites have been constructed on the shores of the dam. The recreational side of the dam is administered by Msinsi Holdings and a **Medium** size staff is employed to maintain the facilities. This is equivalent to 5.36E-06 job units/kL

The water supply function of the dam is administered by Umgeni Water and a **Small** size staff is employed to maintain and operate the dam or 1.78E-06 kob units/kL

The total job creation score for the operation of the dam is Medium which again in terms of the functional unit is 5.36E-06 job units/kL

Decommissioning

It is expected that at the end of the usable life of the dam it will be allowed to fill up. It is possible that the dam wall will be demolished.

The job creation score for this is **Small** (1.78E-06 job units/kL) as not many people are expected to be involved in this operation.

4.3.1.2. Health and Health Risks

As with the job creation category and the LCA, the system is divided into sub-systems and evaluated separately.

Construction

In the particular case of Inanda Dam the largest health impacts can be attributed to the relocation of the residents living in the floodplain of the dam. Most of the residents were originally subsistence farmers. Deprived of their farm land, the high cost of living in urban areas meant a less nutritious diet resulting in malnutrition. Due to lack of planning and preparation residents were moved to areas with inadequate facilities. Members of the amaNgcolosi tribe were dumped in Molweni township in 1987. They have to walk up to 2 km each day to fill buckets from a solitary tap in the area. Previously water was plentiful as the Umgeni River flowed past their homesteads, nourishing the crops and livestock on which they subsisted. At present the communities are still living in the 'temporary' accommodation. Table 4-5 presents some statements by a few representatives of the affected communities which highlight their plight.

Table 4-5: Statements by people relocated during the Inanda Dam development at the Southern African hearings for Communities affected by Large Dams (2000).

Speaking of the relocation:

'We came here as humans, but now we are just animals. We are dying here. Our human nature is denigrated' - Mbikwa Ndlela

'Most of the people are not working – they did not choose this kind of life. It must be remembered that these families have been relying on the land through farming. Nobody received any form of compensation. When the families were moved they were promised houses. Instead they were given tin houses and the tin houses are so close together it is impossible to build extra rooms.'- Paulos Gwala, representative of the amaPhephetha tribe

'We are still living in tin houses. Nobody cares if we boil in the summer and freeze in the winter'- Eunice Msomi

'Until today every promise has been broken. The community feels unheard'- Maxwell Meyiwa

The health impacts have been mitigated by the small size of the community and the favourable environmental conditions of the surrounding areas.

Even though the Inanda Dam project has been spared some of the potentially worse health impacts (as discussed in Section 4.2) it was decided to award this stage a **High** health risk score in view of the impact on the relocated community. This score was based on the present living conditions of the relocated communities where they do not enjoy proper water and sanitation facilities and are forced to live in generally unhygienic conditions.

Operation

There are very few operational hazards associated with the running of the dam. Also the dam is regarded as a non polluter with regards to human health and it was therefore decided to give assign a **Low** rating for this stage.

Decommissioning

Again it is anticipated that the health risks will be low and a **Low** score is awarded.

4.3.2. Wiggins Waterworks, Pumping and Reticulation Network, Southern Wastewater Treatment Works, Durban Water Recycling Plant, Disposal to Sea

The process units constructed for the treatment and distribution of water and wastewater have very similar social impacts and have been grouped together for the purpose of this analysis. The similarities include the low health and health risks scores. One must remember that this study does not consider the impact of potable water or sanitation and the associated benefits. Rather the study looks at the particular technology used to provide these services. The Wiggins Waterworks, Durban Water Recycling Plant, and Southern Wastewater Treatment Works have almost identical social impacts. The construction of the pumping and reticulation network has a **high** job creation score due to the labour intensive nature of the project. It must be noted that water and sewage infrastructure are normally constructed with the roads and other amenities during the development of a new area. Therefore, it is difficult to separate the labour required specifically for the water and sewage construction work.

The health impacts arise from the nature of the work and the impact of the processes on the environment which impact on human health. Here a note must be made of the electricity use of the treatment process. This results in a transferred social impact i.e. the impact is not felt at the site of use rather at the place of generation. The impact on human health caused by the pollution emanating from the coal fired power stations is discussed in greater detail in the next chapter. However, suffice to say the generation of electricity has a detrimental impact on the communities living in Mpumalanga where a large portion of South Africa’s electricity is generated.

A total of 80% of South Africa’s electricity is produced in Mpumulanga. This region has one of the world’s worst dispersal climatologies. Annual emissions of air pollutants such as particulates, sulphur dioxide, nitrous oxides, carbon dioxide, carbon monoxide and hydrocarbons currently exceed 200 million tonnes over this region. The largest contribution to the emissions is from the carbon dioxide formed during combustion. Most of these pollutants come from the power stations though there are substantial contributions from various smaller industries, discard coal dumps and motor vehicles (Huntley et al., 1989).

Table 4-6 shows a breakdown of the gas emissions due to the electricity generation process.

Table 4-6: Gas emissions from the electricity generation and distribution process (Eskom, 2000)

Item	Unit	2000	1999	1998	1997
Nitrogen oxide (NO)	Thousand tons	674	673	669	688
Nitrous oxide (N_2O)	Tons	2093	2010	2031	2085
Sulphur dioxide (SO_2)	Thousand tons	1505	1506	1583	1382
Carbon dioxide (CO_2)	Million tons	161,2	159,4	163	169

Mpumulanga has one of the most polluted atmospheric environments in the country. A wide variety of both natural and anthropogenic sources of air pollution exist in Mpumalanga, ranging from veld fires to industrial processes, agriculture, mining activities, power generation, paper and pulp processing, vehicle use and domestic use of fossil fuels (Mpumalanga Province, 2002) The useful service life of unprotected metals, such as fencing lines and corrugated iron roofs, has been halved in parts of this region. It is therefore, unrealistic to assume that the human body will remain unaffected by the atmospheric pollution. However thus far there is no firm evidence attributing the health impacts directly to power generation. The specific health impacts relating to coal fired power stations are discussed in Chapter 5.

For the Durban Water Recycling plant an environmental impact assessment (EIA), in accordance with the EIA regulation of South Africa's Environmental Conservation Act (Act 73 of 1989), to evaluate potential environmental impacts (biophysical and social) associated with the recycling project was carried out before the construction phase. This legislation was not in place prior to the construction of the other subsystems and therefore, there was not one carried out. The EIA found that there were no significant negative impacts resulting from the project that could be regarded as fatal flaws. The project was characterised as being environmentally positive and was viewed as such by the greater community (Kuck et al., 2002).

Table 4-7 presents a summary of these social impacts associated with job creation for the water network downstream of Inanda Dam and Table 4-8 the social impacts related to health and health risks.

Table 4-7: Summary of the social Impacts of Wiggins Waterworks, Pumping and Reticulation Network, Southern Wastewater Treatment Works, Durban Water Recycling Plant and the Disposal to Sea for the job creation category.

Unit	Construction	Construction (job units/kL)	Operation	Operation (job units/kL)	Decommissioning	Decommissioning (job units/kL)
Wiggins Waterworks	Medium	1.7E-06	Small	5.6E-06	Small	5.6E-06
Pumping and Reticulation	Large	1.3E-04	Medium	3.1E-05	Small	1.0E-05
Southern Wastewater Treatment Works	Medium	1.9E-05	Small	6.3E-06	Small	6.3E-06
Durban Water Recycling Plant	Small	1.6E-05	Small	1.6E-05	Small	1.6E-05
Disposal to Sea	Small	4.2E-06	Small	4.2E-06	Small	4.2E-06

The construction of the pumping and reticulation network is assigned a **large** score owing to the labour intensive nature of the process. Trench digging and pipe laying in South Africa, or any developing country for that matter, usually requires more labour for this type of task than a first world country would. This also carries through to the operations since leaks and repairs have to be manually attended to usually involving a number of labourers. The rest of the scores for the operations phase receive a **small** job creation score due to the highly automated nature of the treatment processes. In this regard the processes used in South Africa are on par with the world leaders. The decommissioning phase is assigned a small job creation score since this occurs over a very short period and not many permanent jobs are created. When quantified in terms of the functional unit the job creation score for the construction and operation of the pumping and reticulation network has the highest score. The highest score for the decommissioning phase comes from the recycling plant. This is due to the fact that in most cases the reticulation pipes are not removed during decommissioning.

As stated earlier the health impacts are mainly due to polluting effects of electricity generation. Table 4-8 presents a summary of these impacts.

Table 4-8: Summary of the social Impacts of Wiggins Waterworks, Pumping and Reticulation Network, Southern Wastewater Treatment Works, Durban Water Recycling Plant and the Disposal to Sea for the health and health risks category.

Unit	Construction	Operation	Decommissioning
Wiggins Waterworks	Low	Medium	Low
Pumping and Reticulation	Low	Low	Low
Southern Wastewater Treatment Works	Low	Medium	Low
Durban Water Recycling Plant	Low	Medium	Low
Disposal to Sea	Low	Low	Low

The construction and decommissioning categories are both assigned low scores due to the relatively low incidence of accidents and health hazards associated with the phases. The sub-systems which receive a **medium** score do so because of their high electrical use.

4.4. Discussion

One of the shortcomings of social impact assessments is that they involve considerable uncertainty and it is difficult to predict the effects for different groups. Thus the impacts and results of this study will not necessarily apply to another region.

South Africa is in the process of considering a new protocol for water resource development as part of the National Water Resources Strategy guiding the implementation of the National Water Act promulgated in 1998. The protocol represents a departure: from the supply side dominated engineering paradigm currently guiding many of the water decisions in our country and in many places in the world toward one that embraces the core principles of integrated resource planning (Naidoo, 2000). The adoption of this protocol will have many positive political, economic and social implications for communities in developing countries as affected communities will be involved in all stages of the development process.

Dams have resulted in loss of land, forests and resources. Fresh water fish have become endangered species, and even extinct. The social impact downstream has been large, and it has been estimated that 60 million people worldwide have been flooded of their land and out of their homes by the construction of dams (Kasrils, 2000). However with this is mind it is not so easy or simple to make a blanket generalisation that dams are bad. Social decision making is problematic because competing individual preferences cannot, in general, be reconciled to produce universally agreed upon social preferences. In addressing the problem of ranking different objectives Hertwich, (2000) stated that in the case of dam construction usually the decision to proceed is based on the ideology that ‘the needs of the many outweigh the needs of the few’, however this does not mean that the few have to suffer.

The culture of forced removals has been replaced in South Africa by one of co-operative involvement. In a recent scheme called the Berg River Project in the Western Cape region, the affected communities were involved in the decision making from an early stage. In fact the final relocation terms proved to be so attractive that even people who were not affected were clamouring to be included (Lianne Greef, personal communication). This is an example of how a dam can have a positive social impact.

For the impacts associated with the other developments most of the health impacts are associated with the use of electricity. This impact is often overlooked as it is not site or process specific impact. Here the advantage of using the LCA methodology is clear and the impact of electricity generation, although occurring hundreds of kilometres away, is included. Until cleaner or alternate technology is used these impacts will persist.

There has traditionally been resistance to environmental legislation as it is perceived to cause job losses (due to the higher costs incurred by the company to comply). However Goodstein (1994) in his book *Jobs and the Environment: The myth of a national trade off* uses over half a dozen macroeconomic studies to show that the economy wide effect of environmental regulation is either negligible or slightly positive (more job gains than losses).

4.5. Conclusions

This chapter has shown how in some cases, particularly Inanda dam, the social impacts outweigh the environmental impacts. There is on-going development into the inclusion of social impact indicators into the formal LCA framework and this will make the LCA tool a more holistic one. Social and environmental impacts cannot be viewed in isolation as more often than not they are interlinked. Thus for any new development, the social and environmental impacts should be analysed in tandem.

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Chapter 5 : The Impact of Electricity Generation in South Africa

The environmental LCA has shown that the use of electricity is responsible for almost 80% (Figure 3-5) of the total environmental burden of the system. Electricity use also has a similarly high social impact. This chapter analyses the generation of electricity in greater detail in order to show where these impacts originate and to highlight the importance of electricity efficiency measures to enhance environmental benefits.

Often when the environmental and social burdens of a process are considered, the burdens of the electricity used in the process are ignored. What this does is ignore the effects of the pollution and health problems that the generation of electricity causes. The LCA methodology however takes these burdens into account.

There are data that are common in all LCIs, namely electricity, transportation and waste management. Electricity use, especially, features very prominently in the total LCA results for a majority of product life cycles. In this chapter Section 5-1 presents a review of the electricity generation process in South Africa and compares this with the electricity impact model used. The impact model used was developed by the Centre for Environmental Studies at the University of Leiden, this model is presented in Section 5-2. This model is based on European coal fired power stations. Section 5-3 examines the environmental impact of power generation in South Africa and the inventory for the impact model used is compared to an inventory for South African coal based power generation. In Section 5-4 the social impacts of coal based power generation are considered. As South Africa is looking to increase its power generation ability Section 5-5 examines alternate methods of power generation and the associated environmental and social impacts.

5.1. Electricity production in South Africa

A total of 95 percent of the electricity used in South Africa is generated by the para-statal power company, Eskom. Eskom has a total nominal capacity of 42 011 MW of which 37 678 MW (88%) comes from coal fired power stations. Figure 5-1 shows a breakdown of electricity production in South Africa. This is unlikely to change significantly in the next decade due to the lack of suitable alternatives to coal and the abundant available supply.

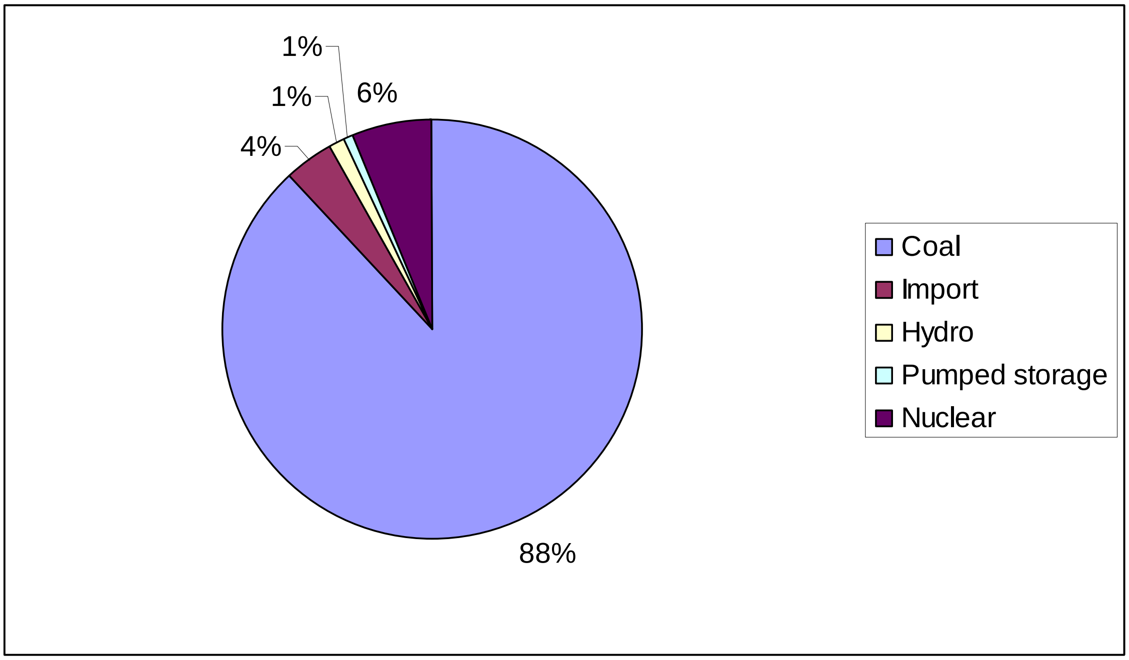

Figure 5-1: Description of the Eskom generation mix (Eskom annual report, 2003)

South Africa produces an average of 224 million tons of coal annually, making it the fifth largest coal producing country in the world. Eskom uses 53 percent of this coal for electricity generation. South Africa's coal reserves are estimated at 53 billion tons and with the present production rate there is an estimated 200 years of supply left.

Eskom cites the following advantages and disadvantages of using coal for electricity generation in Table 5-1.

Table 5-1: Advantages and disadvantages of using coal fired power stations. (Eskom)

Advantages	**Disadvantages**
• SA has abundant coal reserves • Coal fired power stations are reliable • SA's infrastructure to generate electricity from coal is well established. • Burning coal is the most cost effective and energy efficient way of generating electricity in SA.	• Coal has the most waste problems of all energy sources. Waste includes sulphur and nitrogen oxides, organic compounds, heavy metal, radioactive elements, greenhouse gases and a lot of ash. • Building a coal fired power station is a long and expensive process. • SA's coal fields are concentrated in Mpumalanga, which limits the location options for power stations.

Figure 5-2 shows the location of the power stations in South Africa, showing the highly regional placement of the power stations, with only Koeberg nuclear power station in the south of the country, and all but one of the coal-fired stations located within the box.

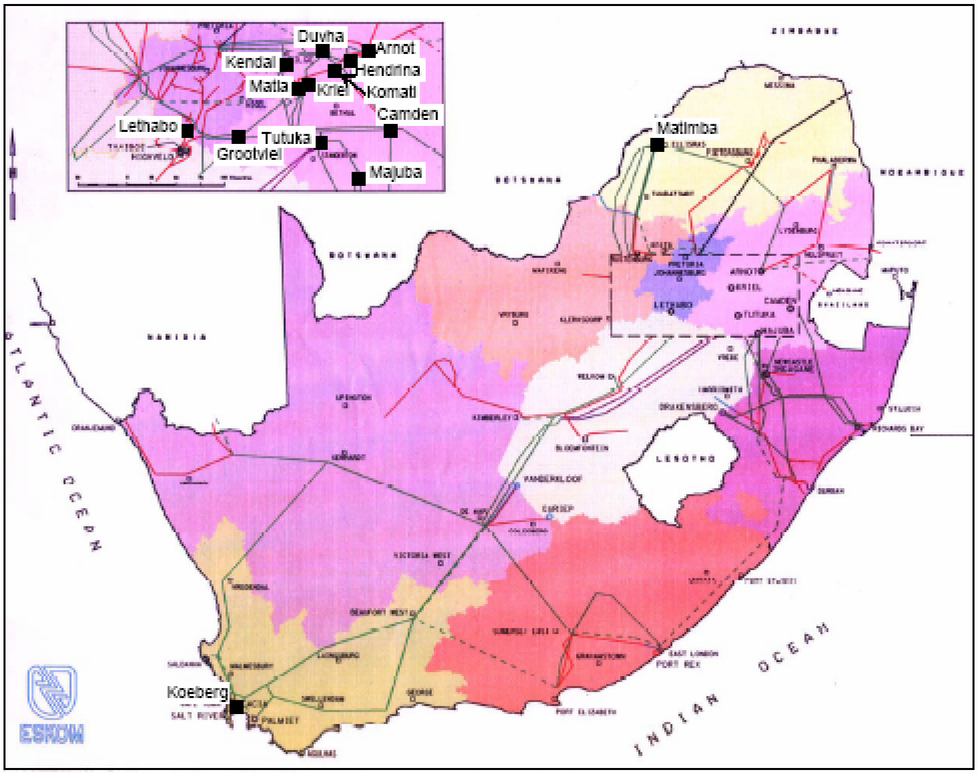

Figure 5-2: Electricity grid map of South Africa (source: Eskom).

The highly localised nature of the power stations immediately suggest that the pollution effects of the power stations are concentrated in this area as will be discussed in Section 5-3.

5.2. Impact model used

The GaBi LCA modelling tool was developed by the Institute for Polymer Testing and Polymer Science (IKP) at Stuttgart University and its spin-off the PE Consulting Group. GaBi 3 version 2 was used in this study and the 'lean' database which it contains is based on data collected from literature sources.

Table 5-2 shows the environmental cost of producing 1 kWh of electricity, taken from the GaBi database.

Table 5-2: Environmental impact of producing 1kWh of electricity (taken from GaBi 3 database version 2)

Category	Mass (kg)
Global Warming (kg CO_2 eq)	1.22E+00
Ozone depletion (kg R11 eq)	2.02E-08
Acidification (kg SO_2 eq)	6.11E-03
Eutrophication (kg Phosphate eq)	3.91E-04
Photo-oxidant (kg ethene eq)	7.60E-05
Aquatic ecotoxicity (kg DCB eq)	1.71E-02
Terrestrial ecotoxicity (kg DCB eq)	1.44E+00
Human ecotoxicity (kg DCB eq)	2.12E-02

5.3. Environmental impacts of Electricity Production in South Africa

According to a national inventory study undertaken with 1988 data, South Africa accounts for 1.4% of global carbon dioxide emissions and 1.2% of total global GHG emissions (Scholes and van der Merwe, 1995). The 1992 Stockholm Environment Institute (SEI) global GHG inventory found South Africa to be the largest source of GHGs in Africa, accounting for 15 % of the continent's carbon dioxide emissions and 11% of the methane emissions (Subak et al., 1992). South Africa is also the largest electricity producer on the continent and a large proportion of the emissions can be attributed to the electricity generation industry.

Coal mining has been a major cause of environmental degradation in South Africa (Van Horen, 1996) and therefore the environmental impacts of the mining contribute significantly to the overall burden of electricity generation. Coal mining, particularly opencast mining, is associated with massive surface disruption. Opencast mining accounts for 45% of South Africa's coal production (Prevost, 1998).

The discard dumps of the coal mines are responsible for some of the most serious environmental effects of coal mining. These include land sterilisation and groundwater contamination. (Notten, 2001)

The location of the coalfields is significant as from a water quality perspective they occur in the worst possible location. Most mines are situated in the vulnerable upper reaches of southern Africa's major river systems (Wells et al., 1992).

This chapter considers only the effects of coal fired power plants as they generate, and will continue to generate, the majority of South Africa's power. The impacts of transmission and distribution are excluded.

The following table shows a less detailed breakdown presented by Eskom of the Environmental implications of using one kilowatt hour of electricity. The emissions have remained relatively constant with the exception of the emissions of ash which have decreased steadily over the years.

Table 5-3: The environmental implications of using one kilowatt-hour of electricity (Eskom)

Category	Unit	
Water usage	l	1.27
Coal usage	kg	0.49
Ash produced	g	132.62
Ash emitted	g	0.29
SO_2 emissions	g	7.56
NO_x emissions	g	3.55
CO_2 emissions	kg	0.89

Notten (2001) compiled a detailed LCI for the South African generating mix. This LCI was based on both the published figures of Eskom and her own calculations. This is presented in Table 5-4 along with the LCI from the GaBi database for a hard coal power generation mix. It was important to carry out this comparison to see how much the model used for the impact assessment stage of the LCA differed from actual South African data. Due to confidentiality issues this study was made public much later than when it was produced and the results could not be used for the current research.

Table 5-4: LCI of the South African power mix (Notten, 2001) and LCI of a hard coal based power mix from the Gabi database.

	SA mix kg per kWh	Gabi mix kg per kWh	Difference
CO	1.50E-04	1.25E-04	16.42%
CO2	1.00E+00	9.79E-01	2.09%
HCl	2.00E-06	3.00E-04	-14909%
HF	1.00E-06	3.19E-05	-3088%
N2O	4.00E-07	6.06E-06	-1416%
Nox	2.70E-03	2.52E-03	6.76%
SO2	8.00E-03	4.02E-03	49.77%
methane	5.60E-05	4.26E-03	-7499%
non methane VOC	1.60E-05	1.00E-04	-525%
As	5.00E-07	1.97E-06	-294%
Cu	2.00E-06	4.89E-06	-144%
Mn	9.00E-06	1.11E-07	98.77%
Pb	4.00E-06	1.83E-07	95.43%
Al (water)	2.00E-06	9.75E-04	-48669%
Chlorides (water)	4.90E-05	6.30E-03	-12761%
Sulphates (water)	1.20E-03	4.35E-03	-262%

The table shows that for the some of the major emissions such as carbon dioxide, nitrous oxides and carbon monoxide the inventories agree closely. The main differences are in the trace emissions such as aluminium to water and chlorides to water. These differences are in part due to the fact that South African power stations do not use flue gas desulphurisation units. European coal power stations use a limestone sorbent and limestone quarry mining is associated with particularly high emissions to water.

5.4. Social impact of electricity production

It is hard to quantify the social impact of electricity production and there is much controversy surrounding this subject. It has been argued that health problems are related to the poor air quality in the region of the power stations. However Eskom cite the fact that electrification reduces air pollution in the region as a result of decreased biomass and coal burning for domestic heating and cooking (Eskom, 1996b). Holdren and Smith (2000) agreed with this and showed that exposure to indoor air pollution is one of the most important energy related environmental and health problems facing developing countries. In South Africa it is clear that the health impacts of household fuel use -including exposure not only to pollution but also to fire and poisoning hazards from paraffin- are significant problems for poor communities (Mehlwana, 1999; Spalding-Fecher et al. 2000)

In a study undertaken by Eskom it was shown that if desulphurisation plants were installed at all the coal fired power stations, the cost of electricity would go up by 20 percent. At the same cost one could provide electricity to approximately 240 000 people living in township areas. This would benefit the environment more as one of the main sources of pollution is coal fires used by people in townships for their energy requirements. However the air quality has deteriorated to such an extent that the CAPCO (chief air pollution control officer) has “capped”emissions in the region forcing Eskom to explore coal-fields further afield.

This section will address the social impacts based on the impact categories described in Chapter 4.

5.4.1. Job Creation

Eskom is one of South Africa’s largest employers with almost 30 000 permanent employees. There is a strong commitment from Eskom to follow the government’s employment equity policies and thus there is a good distribution of women, people with disabilities and black staff across all levels of the company. Thus the job creation score for this category is **Very large.** However, if one examined the energy used by the system that is used exclusively for the water and sanitation processes, this score is reduced. Approximately 10 to 15 MW is required to provide power for the water and sanitation proceses used by the eThekwini Municipality. If this power was bought from an independent power producer that yielded only this small amount of electricity then of course there would not be as many people employed and the job creation score would drop to **Small**.

5.4.2. Health and Health Risks

The main health impacts of power generation occur due to the air pollution resulting from the power station emissions. The analytical challenge is that there is no national level quantitative data on any of these impacts in South Africa (Spalding-Fecher, 2005). Table 5-5 summarises some of the important health impacts that can be attributed to these emissions.

Table 5-5: Impact of burning fossil fuels to generate electricity (CEROI, 2005)

Pressure	Source	Effect
Carbon dioxide and carbon monoxide	Burning of fossil fuels Incomplete combustion in motor vehicles	Reduction in the ability of the circulatory system to transport oxygen; Impairment of performance on tasks requiring attention; Aggravation of cardiovascular disease
Suspended particles	Burning of fossil fuels	Damage to lung tissues causing respiratory disease
Sulphur dioxide	Burning of fossil fuels Untarred roads Mining dust Agriculture	Causes constriction of the airways in people with asthma, repeated exposure causes a condition similar to bronchitis Increased risk of acute respiratory disease
Nitrous oxides	Burning of fossil fuels	Can irritate the lungs, aggravate the condition of people suffering from asthma or chronic bronchitis

Locally the health and health risk score is considered to be **High** due to the adverse pollution effects but nationally the benefits of electricity, especially for rural communities, is considered to outweigh the negative effects.

5.5. Alternative technology scenarios

It is useful to consider how the environmental and social impact of the system would change if the generation mix in South Africa was different. The South African energy sector has historically been at the centre of the country's development. From the origins of the electricity supply industry in the first years of the twentieth century – driven by the needs of the booming mining industry- to the more calculated decisions of the apartheid government in the 1950s to develop a synthetic petroleum industry and a local nuclear capacity, to the present focus on widening households' access to electricity, the energy sector has been at the heart of structural developments in the economy (Spalding-Fecher et al., 2000). With the present government committed to implementing sustainable development and showing an increasing interest in nuclear energy generation technologies, it is important to understand the environmental implications of different technologies. As has been shown in Chapter 3, electricity usage accounts for almost 80% of the operational environmental burden for most of the subsystems.

This burden could therefore be significantly reduced if a cleaner generation technology was used.

This section presents the impacts of a few new and in some cases, cleaner technologies that would be able to work in South Africa. In fact some of the technologies are already being investigated by Eskom for future development. One can view this section as a pseudo improvement analysis for electricity generation as it examines options in a similar fashion to Chapter 3-4.

5.5.1. Wind Energy

A study by Arpad Horvath of the University of California which investigated only the global warming effects (GWE) of different generation technologies highlighted the superiority of using wind generation. Figure 5-3 shows the results from this study.

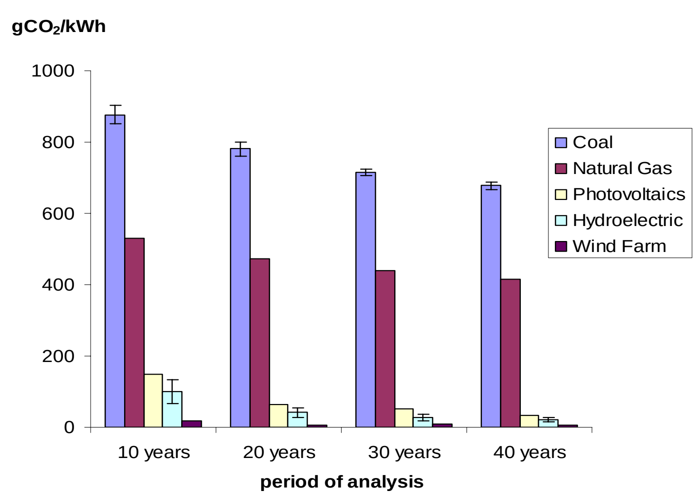

Figure 5-3: GWE normalized by electricity output for various alternatives and four time periods after construction. (Pacca and Horvath, 2002)

Wind energy has a large potential to create jobs. A study by the Australian Wind Energy Association (AusWEA) showed that 9.9 direct job years are created per MW of installed wind energy over the project life of a wind farm.

5.5.2. Coal – biomass based electricity production

In a study in France (Bennetto et al., 2004) showed that by using a combination of short rotation coppices (SRC) the environmental impacts of electricity generation could be greatly reduced. A combination of coal and SRC, 68% and 32% by weight, was utilized as a fuel in a standard coal power station with minor modifications. The study showed the following comparisons with a traditional coal fired power station

For the impact category of ‘abiotic resource depletion’ the impact was one fifth that of the traditional station, for climate change’ one third and ‘human toxicity’ and ‘ecotoxicity’ 20 times lower. In particular the carcinogenic effects on humans are reduced to almost zero. ‘Photo-oxidant’formation is also less than half. These results demonstrate that biomass co-combustion significantly reduce the impacts of a coal fired power station.

Rafaschieri (1999) in a similar study on the impacts of electricity production from poplar energy crops compared with conventional fossil fuels showed similar results. The study showed that with reference to the biomass production, the most negative environmental impacts are caused by the usage of chemicals and fertilisers. The study also highlighted the important social impact on the rural economy especially where labour intensive methods are used.

In a paper on bio commodity engineering Lynd (1999) concluded that plant biomass is the only foreseeable sustainable source of organic fuels, chemicals and is one of a limited set of potentially sustainable resources that could be used as a source of energy for transportation and power generation (Lynd et al., 2003)

5.5.3. Nuclear fuel

The ExternE project undertook a study to compare various methods of electricity generation. The study considered both health and environmental burdens and used life cycle methodology. The results showed that the nuclear fuel cycle allows minimization of CO_2 emissions thus taking the lead in combating the greenhouse effect. The health impacts resulting from the emissions of chemical pollutants such as SO_2, NO_x, nitrates and sulphates are also clearly reduced with the nuclear option. The study concluded by saying ‘the nuclear option is not only a major actor in the worldwide energy market, but also a major contributor to the preservation of health and the environment’. Figure 5-4 shows the emissions from the different fuel cycles.

Nuclear power generation produces no carbon dioxide emissions, smoke or any other gases. In France, carbon dioxide emissions from electricity generation fell by 80% between 1980 and 1987 as its nuclear capacity increased . In Germany the nuclear power programme has saved the emission of over 2 billion tons of carbon dioxide from fossil fuels since it began in 1961 (PBMR, 2005)

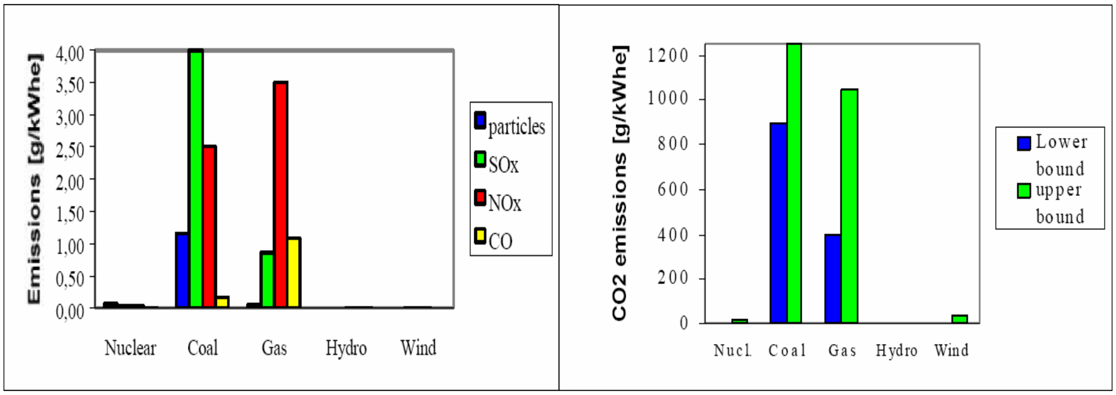

Figure 5-4: Key results from the ExternE study showing the emissions from the different generation technologies studied.

Currently in South Africa there is much interest in the pebble bed modular reactor type nuclear fuel technology. These 'pocket size' reactors are seen as the expansion method of choice by Eskom. However this has been met with much protest due to the increased amounts of nuclear waste that is produced.

The most contentious point in the nuclear energy debate is the handling of the spent nuclear fuel. If a proper waste management program is in place there are negligible radiological impacts. The problem arises when the spent fuel has to be transported great distances to a treatment facility and the possibility of an accident arises.

Thus the health risks associated with the nuclear fuel option are regarded as being **high**. This is because even a small accident could prove to have catastrophic effects.

5.5.4. Small hydro

Small hydro is defined as a technology that transforms water energy into mechanical work that, by moving a turbine connected with an alternator, generates up to 10MW. Small hydro is seen as an alternative to the construction of large dams and thus does not have all the associated environmental and social impacts.

The conclusions of the ExternE study agree with a similar study in Spain (AUMA, 2000). Again the study was performed using LCA methodology and the ecopoint method was used to evaluate the environmental impacts using the Simapro software. This study was carried out in order to assess the potential impacts of small hydro power stations.

The study showed that in general, renewable sources of energy have a lower impact than conventional methods of generation. Figure 5-5 shows the results of the study. The results showed that the impact of conventional technologies was 31 times higher than that of renewable energy sources. The best renewable technology was small hydro which had an environmental impact 250 times lower than that of coal generation.

Impacts/Energetic Systems	lignite	Coal	Fuel-oil	Natural Gas	Nuclear	Wind	Smallhydro
Global Warming	135.00	109.00	97.00	95.80	2.05	2.85	0.41
Ozone Layer Depletion	0.32	1.95	53.10	0.86	4.12	1.61	0.05
Acidification	920.00	265.00	261.00	30.50	3.33	3.49	0.46
Eutrophication	9.83	11.60	9.76	6.97	0.28	0.27	0.06
Heavy Metals	62.90	728.00	244.00	46.60	25.00	40.70	2.58
Carcinogenic Substances	25.70	84.30	540.00	22.10	2.05	9.99	0.76
Winter Smog	519.00	124.00	135.00	3.08	1.50	1.48	0.15
Summer Smog	0.49	3.05	36.90	3.47	0.32	1.25	0.06
Radioactivity	0.02	0.05	0.02	0.00	2.19	0.01	0.00
Industrial Wastes	50.90	12.90	0.62	0.58	0.28	0.29	0.52
Radioactive Waste	5.28	10.60	7.11	1.34	565.00	1,83	0.32
Depletion of Energy Sources	5.71	5.47	13.60	55.80	65.70	0.91	0.07
TOTAL	1735.15	1355.92	1398.11	267.11	671.82	64.67	5.43

Figure 5-5: Results of Spanish study on the impacts of different methods of electricity generation. (AUMA, 2000)

One of the downsides of small hydro is that large projects tend to be more efficient in terms of resource use in hydro schemes associated with the construction of a dam.

5.5.5. Hydro Power

Hydro power generally involves the construction of a dam which supplies water to a power generation facility. More often than not the dam is also used to supply water for irrigation, potable water treatment supply and for flood control. There is a lot of controversy surrounding the environmental impact of dams and this has been dealt with in chapter 3 regarding the impact of Inanda Dam.

An LCA study conducted in Canada showed that hydro power outperformed coal fired electricity generation by a factor of over a hundred when emissions were considered (Gagnon, 2002), however this contrasts with the findings of Brazilian researchers who showed that in some cases the emissions from a hydroelectric power plant can be greater than that of a similar size coal fired plant (Rosa, 2000). This scenario can happen when the flooded area of the reservoir for the power station is covered by dense forest. The emissions from the decomposition of the forest can be large.

The environmental impacts associated with the construction of a dam are dealt with more thoroughly in Appendix 1.

5.6. Discussion

Electricity is a major consideration in any LCA. It is therefore important to accurately calculate and model the activities related to the generation and distribution of electricity. Modeling of the environmental burdens of electricity production is far from a simple or straightforward task since the electricity supply system is among the most complex of all industries addressed in an LCA (Curran et al., 2004). Table 5-6 highlights some of the factors that are responsible for the complexity of modelling the environmental impacts of electricity production.

Table 5-6: Factors influencing the complexity of modelling the environmental impact of electricity production (Curran et al., 2004)

- The broad geographic scope of power grids and electricity markets with power wheeling
- The dynamics of supply despatch in response to demand changes, overlaid on daily and seasonal dynamics
- The wide variation among generation stations in emissions and inputs per unit generation across and even within fuel types
- The rapid ongoing evolution and regional variety of the electricity system and the regulatory environment in which it operates
- The rapid and ongoing evolution of electricity generation technologies and uncertainties about future market penetration of new technologies
- The potentially long time frame and importance of electricity consumption for the life cycles of durable products

The alternate technologies presented in Section 5-5 have the potential to displace coal based generation of power. Lynd and Wang (2004) have derived a set of equations to calculate exactly how much fossil fuel equivalents can be displaced by using biomass to generate energy. These are of course highly dependent on the type of biomass being used but can accurately predict the amount of crops required to be planted in order to achieve a certain power yield.

In South Africa the question is not whether but when alternate sources of power generation will be used.

A study on the environmental impacts of electricity generation (Devezeaux, 2000) also highlighted some of the social impacts of electricity generation. When considering the health impact category for comparing different generation technologies an indicator of deaths per TWh electricity produced was used. The study compared both the occupational and public health impact of the different fuel cycles for nuclear, coal, gas, hydro and wind generation technology. The results (as shown in Table 5-6), clearly show that with regards to both occupational and public health, coal generation is by far the worst. Hydro and wind generation technologies had the best results.

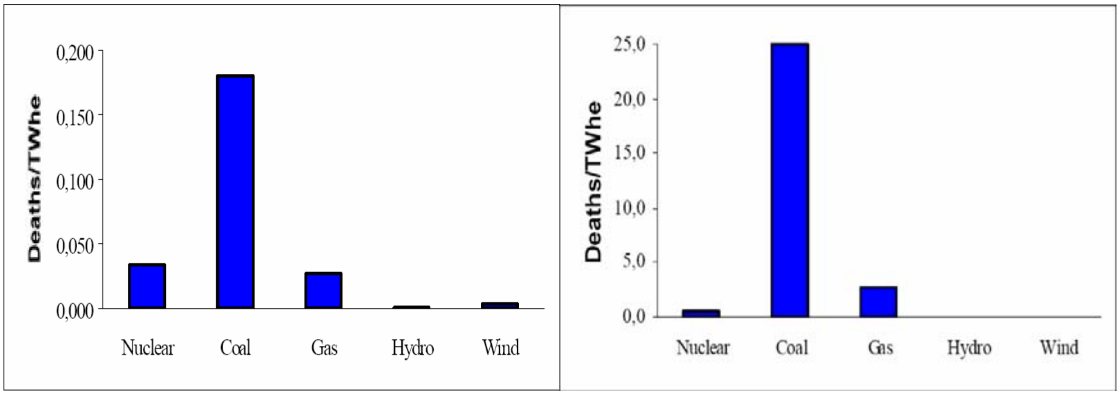

Figure 5-6: Health impact of the different fuel cycles. (Left: Occupational; Right: Public) (Devezeaux, 2000)

Job Creation

A study by the Renewable and Appropriate Energy Laboratory of the University of California (Kammen et al., 2004) quantified the jobs created by different methods of electricity generation The difference between the job unit in this study and that used for the social analysis of Chapter 4 is that each job unit is 32.5 years. The results are presented in Table 5-7.

Table 5-7: Average employment for different energy technologies. "MWa" refers to average installed megawatts de-rated by the capacity factor of the technology; for a 1 MW solar facility operating on average 21% of the time, the power output would be 0.21 MWa (Source: Kammen et al., 2004)

Energy Technology	**Average employment over life of facility (job/MWa)**		
	Construction, manufacturing and installation	**O&M and fuel processing**	**Total employment**
Photovoltaic 1	6.21	1.20	7.41
Photovoltaic 2	5.76	4.80	10.56
Wind 1	0.43	0.27	0.71
Wind 2	2.51	0.27	2.79
Biomass – high estimate	0.40	2.44	2.84
Biomass – low estimate	0.40	0.38	0.78
Coal	0.27	0.74	1.01
Gas	0.25	0.70	0.95

Again coal based generation performed poorly with one of the lower job creation scores. One of the key findings of the study was that the renewable energy sector generates more jobs than the fossil-fuel based energy sector..

5.7. Conclusions

Although the benefits of electrification cannot be ignored, that is not the focus of this analysis. Instead the means of providing this electrification to all South Africans and the associated environmental impacts is the subject of discussion. It is clear that coal based power generation has the highest social and environmental burden and therefore South Africa should look to alternate methods to increase the generation capacity. The environmental impacts from water and wastewater treatment are directly proportional to the electricity used. Therefore for future developments one should either use processes that are more efficient or incorporate a cleaner generation technology. In wastewater treatment works where anaerobic digesters are used, the methane generated should be captured and used to generate electricity.

Friedrich and Pillay (2005) proposed the use of an electricity indicator to measure the environmental performance of water and wastewater treatment processes. The amount of energy expressed as kWh/kL of water (potable or wastewater) is enough to simplistically judge the overall environmental performance of existing water systems. It is also a relatively easy index to use from the point of view of the technical staff involved in operating water plants and pumping stations and which usually are not familiar with global warming and CO_2 equivalents. The use of an electricity index would be a good measure, as long as the underlying data (i.e. electricity consumption) can be measured reliably and assigned to different operations or processes. For some municipalities this is not always the case. In this study it took a lot of time and effort to get satisfactory electricity data. The other instance where this index is inappropriate is when the topography of a municipality allows for water systems in which pumping is not required.

This chapter has examined the current method of electricity generation in South Africa and compared it to the model used when calculating the environmental impacts. This was important as the model had to be accurate due to the large contribution of electricity. Since there are a number of cleaner generation technologies being developed which might see use in the near future, these were also investigated.

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Chapter 6 : Use of LCA in planning water and sanitation infrastructure

Apartheid policies left South Africa with a great disparity in wealth and access to both services and natural resources. Large sections of the black community had no access to basic services. It was estimated that at the time of the first democratic elections at least 12 to 14 million South Africans did not have access to potable water (Schreiner, 2000).

As part of the Government's strategy to alleviate poverty in South Africa a policy for the provision of a free basic level of services has been established. A state of the nation address announced that "the provision of free basic amounts of electricity and water to our people will alleviate the plight of the poorest among us" (Mbeki 2001). This led to a new policy to provide 6 000 l of safe water per household per month (Kasrils, 2001). Linked to these policies is a basic sanitation policy. This requires that a basic level of sanitation, defined as a system for disposing of human excreta, waste water and rubbish which is affordable, easy to maintain and environmentally acceptable, be provided to every household.

However, by 2005, 3.6 million people still lacked any access to an adequate level of water supply (Sonjica, 2005). If the infrastructure is not present, the provision of a free basic supply cannot occur. Therefore the continued extension of adequate water supplies to unserved households remains at the core of providing free basic water. The primary intended recipients of free basic water are poor households. In the eThekwini Municipality one of the main contributing factors to increased water demand is rapid urbanisation.

The statistics on the sanitation side are worse. There are 18 million South Africans (in 3 million households) who do not have access to basic sanitation (DWAF, 2002). An estimated 15% of clinics and 11.7% of schools are without sanitation. Many other schools use pit latrines that are inadequate, dirty and unsafe. The government aims to wipe out the sanitation backlog by 2010.

Different scenarios for increasing the water supply of a municipality are discussed in this chapter. The environmental impact of each scenario is also investigated. This chapter opens with a brief description of the scenario analysis methodology in Section 6-1. The assumptions are stated and the different scenarios considered are presented. Section 6-2 considers the base case which considers the status quo. Before changes or modifications can be made for other scenarios it must be asked whether the current system is operating efficiently and if not what can be improved. This is examined in this section. This analysis suggests changes to the way the system is operated to give a better environmental performance. Section 6-3, 6-4 and 6-5 look at the other options that have been considered. The chapter ends with a discussion in Section 6-6 where the results and insights that have been gained are expanded to consider three hypothetical municipalities facing water shortages.

6.1. Introduction to scenario analysis

There are many ways of increasing the potable water supply. Two scenarios were considered in this chapter. Both scenarios consider an increase of 200 000 new customers to the eThekwini Municipality's water and sanitation network. The figure of 200 000 was selected due to the fact that the recycling plant built in Durban has the capacity to free up 40ML/d of potable water supplies, this translates to free basic water for 200 000 customers. The first scenario, Scenario A, considers the case where the new customers are in an urban environment such as Cato Manor township. Scenario B considers the case where the new customers are in a rural environment. The difference between the two scenarios is the type of sanitation provided. eThekwini Water Services (EWS) has defined a 'waterborne edge', beyond the boundaries of which there is no waterborne sewage and on-site sanitation must be provided by the householder. The eThekwini Municipality has a population of 2 749 000 (Municipal Demarcation Board, 2001). The bulk water is supplied to the city by Umgeni Water (790 ML/d). 63 000 households have been identified as having inadequate levels of water and sanitation. A five year target has been set to reduce the sanitation services backlog by 25% and to reduce the backlog in potable water supply by 100% by 2007 (ETM Business Plan, 2003).

Thus in Scenario A the new customers are provided with sewered toilets whilst in Scenario B on-site sanitation is provided. For each scenario three options were considered for the EWS to meet the increased demand. The first option looks at maximising the performance of the existing infrastructure to meet the increased demand. The second option investigates the construction of new infrastructure and the third option is to recycle water for use by industrial customers to free up existing potable water supplies. When considering each scenario and option the impact assessment scores of the provision of services to 200 000 new people were used and not the difference in the inventories. All the options were compared relative to a base case. This is a hypothetical system that was selected to represent the typical supply of water and sanitation currently being used in the eThekwini Municipality. It is fully described in Section 6-2.

In order to model the scenarios a systems approach was used. This approach, as defined by Emery (1969), is a way of considering phenomena or objects as wholes. Thus each scenario was evaluated as an entire system. This allows one to gain a complete understanding of the system. Holism is a key tenet of systems thinking that embodies the idea that an object or phenomena can only be fully understood in its entirety, as a whole, and that to break it down to pieces risks missing critical characteristics (Bell and Morse, 1999).

Systems thinking involves a hierarchical understanding of systems within systems (Kay and Foster, 1999). Systems thinking is fundamentally different from more conventional 'scientific thinking' as conventional scientific understandings and methods are reductionist while systems thinking incorporates reductionist understandings but is holistic (Bell and Morse, 1999).

Kay et al. (1999) argue that the challenge of sustainability is fundamentally a systems problem and that it will inevitably involve complex systems. Systems are inherently subjective as any system is dependent on an observer or group of observers for implicit or explicit definition.

In terms of sustainability, Schmidt-Bleek (1993), Von Weizsacker et al. (1997), Ayers (1998) and others stress that production systems are best understood in terms of the services they provide rather than the material commodities that are produced. Thus it was decided to select a functional unit that described the service provided by each scenario.

There are other ways of defining the services provided by an urban water system. Larsen and Gujer (1997) defined such a system in terms of the provision of public, nutrient recycling services and 'cultural' services in the form of parks, fountains and ponds.

This type of LCA style scenario analyses has been used in the water and wastewater treatment context before. Some examples are Mels et al (1999) when considering scenarios in the development of new sewage treatment methods, Dennison et al. (1998) when assessing management options for wastewater treatment works in the context of life cycle assessment and Fane et al (2004) when examining expansion options for Sydney water

When considering the impacts of each scenario the functional unit was defined as the provision of water and sanitation to 200 000 consumers per day. These consumers are ones who previously have had no access to water and sanitation and will receive the basic level of service as described by the eThekwini Municipality (ETM, 2003). This level of service provides each household with 200 litres of water and a basic level of sanitation service as defined by the National Sanitation Policy (1996). This basic level of service for a household means a VIP (Ventilated Improved Pit) latrine (in its various forms, to agreed standards) or its equivalent in terms of cost, robustness, health benefits and environmental impact; together with ongoing exposure to readily understandable information about correct hygiene practices. In the eThekwini Municipality the method of on site sanitation is the urine diversion (UD) toilet. A full explanation of the workings of this system is presented in Appendix 4.

6.1.1.1. Scenario analysis using LCA for water and wastewater treatment

Water and wastewater treatment has expanded quantitatively and qualitatively over a relatively short period of time due to the large influx of people into the cities. Existing treatment systems often seem highly efficient when described in the traditional manner, focusing on specific quality parameters. Given the long term need for ecological sustainability, the goals for urban water systems need to move beyond the protection of human health and receiving waters to include minimising loss of scarce resource, reducing the use of energy and water, reducing waste generation and enabling the recycling of plant nutrients (Lundin et al., 2000). This study examines the environmental impacts of each scenario and identifies the processes with high environmental burdens. Other technologies or modifications are suggested to reduce these burdens.

Tillman (2000) termed this method of evaluating environmental impacts a *perspective* LCA, where the effects of changes in the treatment process are modelled. It also contains some elements of a *retrospective* LCA since the recycling scenario has already been adopted and operating data has been used to model the impacts. This does not differ with the methodology stated in Section 3.1.1.1 which states that the consequential LCA methodology would be used. This method allows one to assess the impact of changes to a system and evaluate the consequences. To give the reader clarity on the issue of perspective and restrospective and consequential and attributional LCAs the following extract from *the International workshop on electricity data for life cycle inventories is included (Curran et al, 2005)*

…the group noted that retrospective LCIs are LCIs about prior situations or changes/decisions which occurred in the past, while prospective LCIs are about future situations or changes/decisions. An LCI can therefore be prospective attributional (how will things be flowing

in the future?), prospective consequential (how will a future decision change flows?), retrospective attributional (how were things flowing in the past?) and retrospective consequential (how did a prior decision change the flows?).

One of the problems with scenario analysis is that often there may be a number of options and possibilities for improvements and it is not always obvious which combination represents the optimum solution. Another problem is that there may exist more than one optimum solution for improving the systems performance in which case the issue becomes that of choosing the best compromise option from a number of optimum solutions (Azapagic, 1999).

LCA is not the only tool that can be used for this type of analysis. Others such as ; methodology for environmental impact minimisation (MEIM) (Pistikopolous, 1995), waste reduction algorithm (WRA) (Mallick, 1996) and environmental fate and risk assessment (EFRAT) (Shonnard, 2000) exist. There are also specific tools such as that developed by the Argonne National Laboratory (Wang, 1999) which developed the greenhouse gases, regulated emissions, and energy use in transportation (GREET) model to assist the selection of fuel and transportation technologies to reduce emissions of VOCs, CO_2, NO_x, SO_x and PM_{10} (particulate matter less than 10 μm in diameter). Romero-Hernandez et al. (Romero-Hernandez, 1998) developed a framework for evaluating wastewater treatment technologies based on economic and environmental objectives.

When considering the scenarios only the impact assessment scores for global warming were used due to two reasons. Firstly, global warming emissions are closely correlated with the use of electricity and this is the process that causes most of the environmental impacts (see Chapter 3). Secondly, global warming is being currently prioritised as an important environmental impact, locally and internationally. Internationally the Kyoto Treaty became effective in February 2005 and this opens a new market for carbon credits in which South Africa may participate. Following these international trends, a new local carbon credit scheme is being planned to be introduced. Based on the results from the LCA of the system, the emissions of greenhouse gases are a reliable measure of the overall environmental impact of water and wastewater treatment processes. Three options were considered for each scenario, Table 6-1 presents a summary of the options and scenarios that are considered in this chapter.

Table 6-1: The two scenarios considered and the associated options with each scenario which is to provide 200 000 new urban households with water and sanitation services.

Scenario A: 200 000 new customers in an urban environment – waterborne sewage			
	Option 1: Maximise use of existing assets Increase the throughput of the current infrastructure to maximum capacity	**Option 2: Recycle water** Recycle sewage and wastewater for use by industrial customers, freeing up potable water supplies	**Option 3: Build new infrastructure** Construct new infrastructure to meet increased demand.
New infrastructure required	None	Water recycling plant (secondary and tertiary treatment)	Construct new waterworks, dam and associated pumping and piping network
Process units	Dam, waterworks, pumping and reticulation network, primary treatment sewage works.	Dam, waterworks, pumping and reticulation network, primary, secondary and tertiary treatment.	New dam, waterworks pumping and reticulation network, and primary sewage works.
Scenario B: 200 000 new customers in a rural environment – on site sanitation			
	Option 1: Maximise use of existing assets	**Option 2: Recycle water**	**Option 3: Build new infrastructure**
New infrastructure required	None	Water recycling plant (secondary and tertiary treatment)	Construct new waterworks, dam and associated pumping and piping network
Process units	Dam, waterworks, pumping and reticulation network, on-site sanitation.	Dam, waterworks, pumping and reticulation network, primary, secondary and tertiary treatment.	New dam, waterworks pumping and reticulation network, on-site sanitation.

Figure 6-1 presents the flowsheet of each option in scenario A and Figure 6-2 the flowsheet of the options in scenario B. Each block in the flowsheet has the following format

<table>
<tr><td colspan="6">Unit Name</td></tr>
<tr><td colspan="2">Flow in
(Ml/day)</td><td colspan="2">Flow out
(Ml/day)</td><td colspan="2">% losses</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
</table>

The units are presented in their flow order. Therefore the outflow from one unit should be equal to the inflow to the next unit unless there are losses. These losses are generally due to leaks or grey water losses.

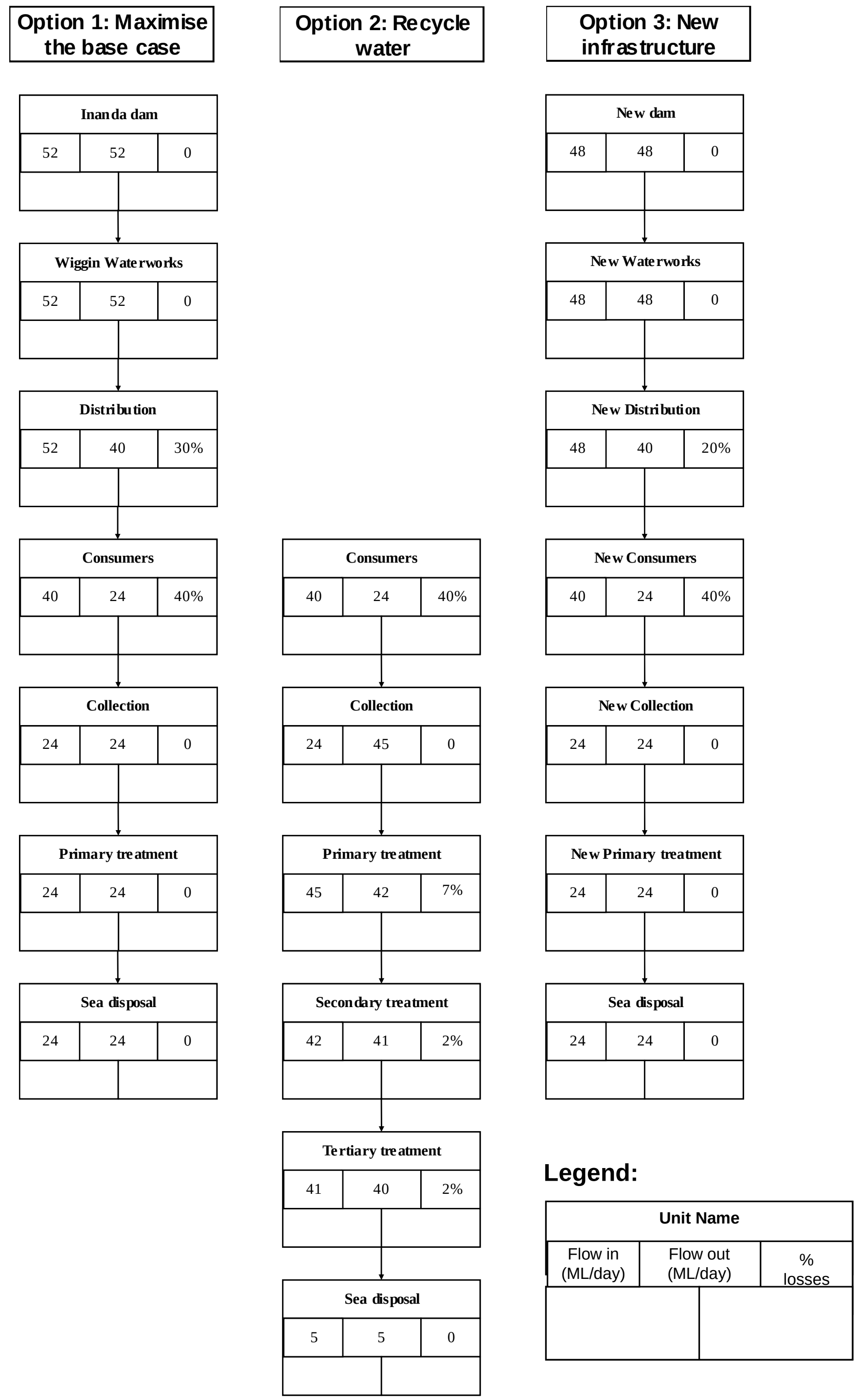

Figure 6-1: The three options for Scenario A (water borne sewage), which is to provide 200 000 new urban households with water and sanitation services. These values are relative to the base case

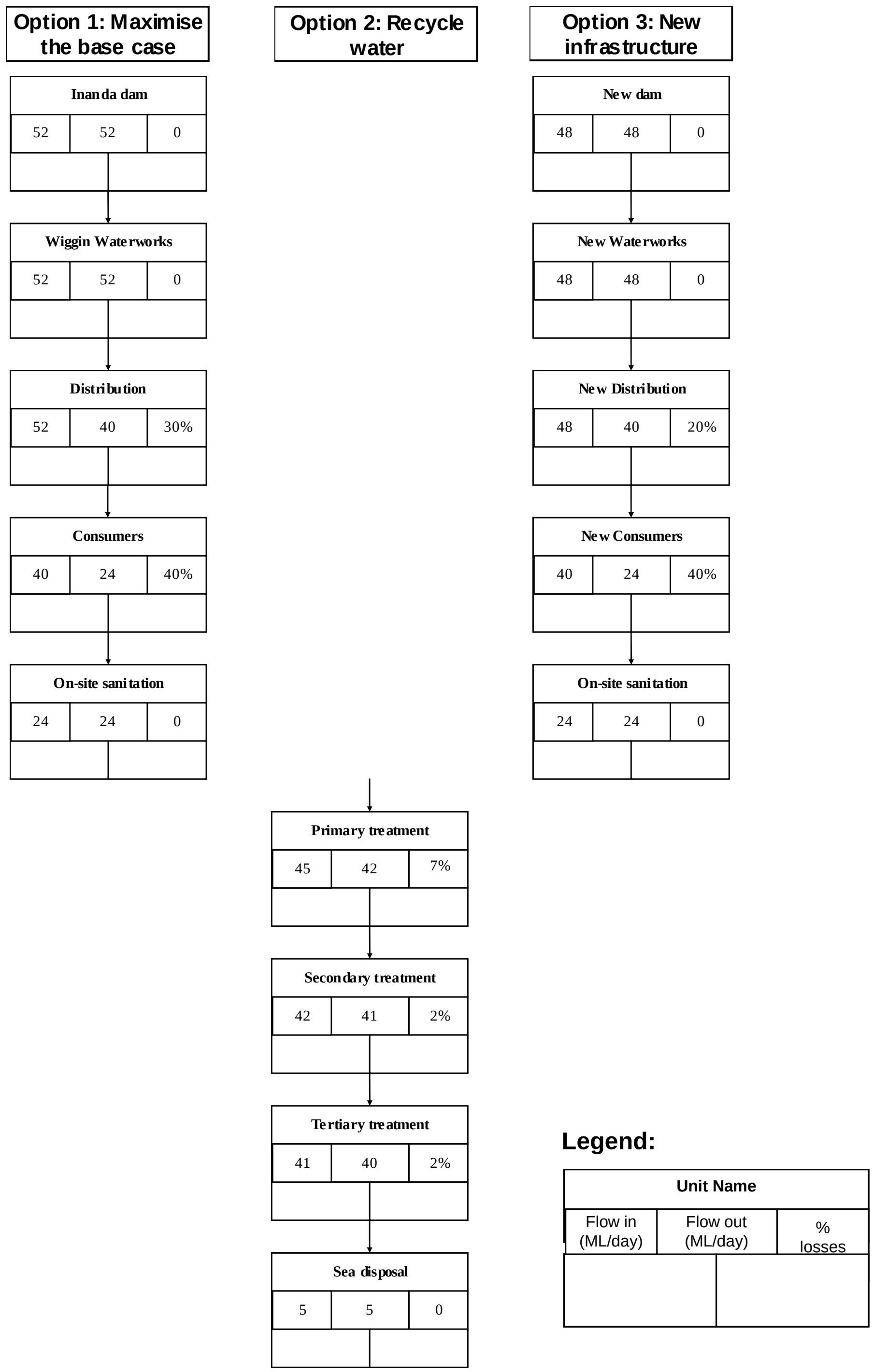

Figure 6-2: The three options for Scenario B (on-site sanitation), which is to provide 200 000 new rural households with water and sanitation services. These values are relative to the base case.

It must be remembered that each option has the capacity to provide different amounts of water. There is a limit as to how much the present assets can be maximised, also the volume of sewage that is viable for recycling limits the amount of water that option 2 can produce. Another important factor that one must remember is that in a large city like Durban, there is a great deal of uncertainty regarding future demand, therefore to ensure that there are no shortages, planners must over design the available supply. Inevitably this leads to excess capacity and hence to inefficiencies. The maximum additional capacity for each option is presented in Figure 6-3.

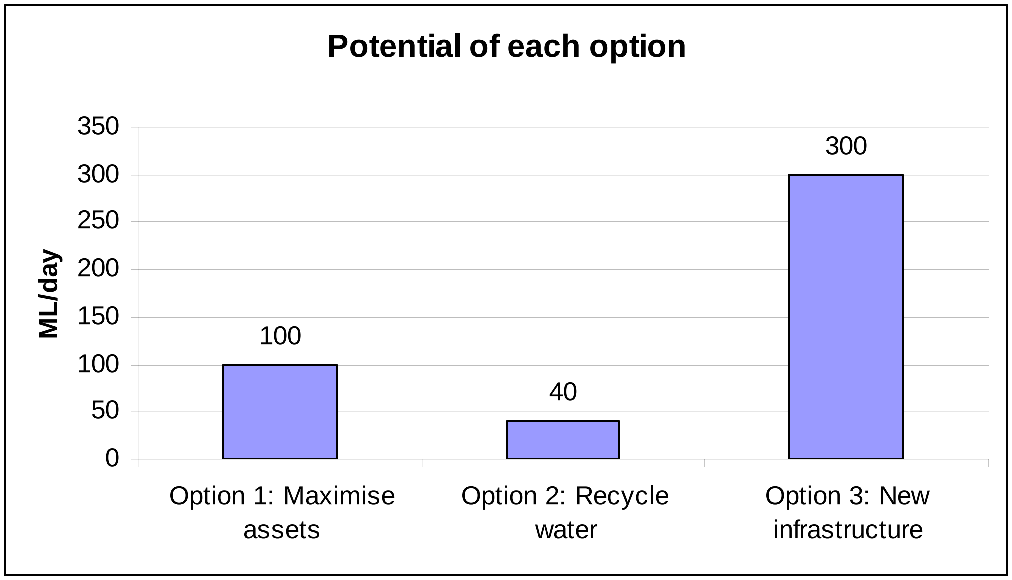

Figure 6-3: The potential additional amount of potable water that each option can produce.

6.1.1.2. On-site sanitation treatment methods

The method of choice for the on-site sanitation treatment systems is the urine diversion toilet. A full description of the workings of this sub-system as well as the potential environmental impacts are presented in Appendix 4 What is important for this chapter are the environmental impacts pertaining to global warming that can be attributed to this sub-system.

The emissions from the UD toilet discharge are small. Bengtsonn (1997) showed that the emissions are largely due to ammonia released from the urine during the spreading. Large variations in these emissions are likely to occur, since this is very much dependent on a number of factors that are hard to control such as climate and wind. For the purposes of evaluating the scenarios the emissions pertaining to global warming were considered. Bengtsonn showed that these emissions are relatively small and accrue mainly from the transport of the urine to nearby farms. Since the urine is used on-site in Durban it was assumed that the emissions of global warming gases were negligible and hence the score for this category is zero.

6.2. Base case

The base case is representative of the existing water and sanitation supply system in Durban. Hence there is no secondary treatment plant included. Secondary treatment is not necessary for coastal discharge, it is necessary when the discharge is into a river in the case of an inland scenario. Chapters 3 and 4 have covered the environmental impacts of the base case in detail and a summary is presented here for comparative purposes. Figure 6-4 shows a simplified flowsheet of the base case. In the bottom left of each box the total global warming impact of each unit is shown and in the bottom right the impact per kilolitre (all in carbon dioxide equivalents)

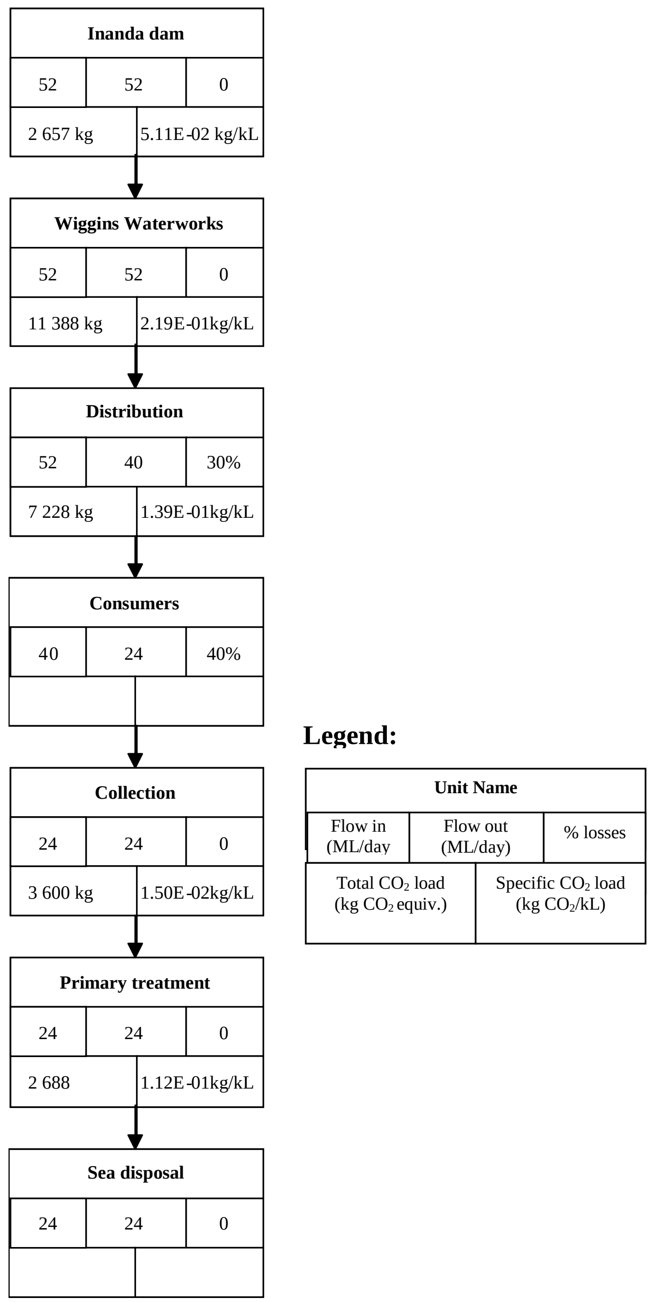

Figure 6-4: Simplified flowsheet of the base case.

The environmental impacts of the base case are presented graphically in Figure 6-5.

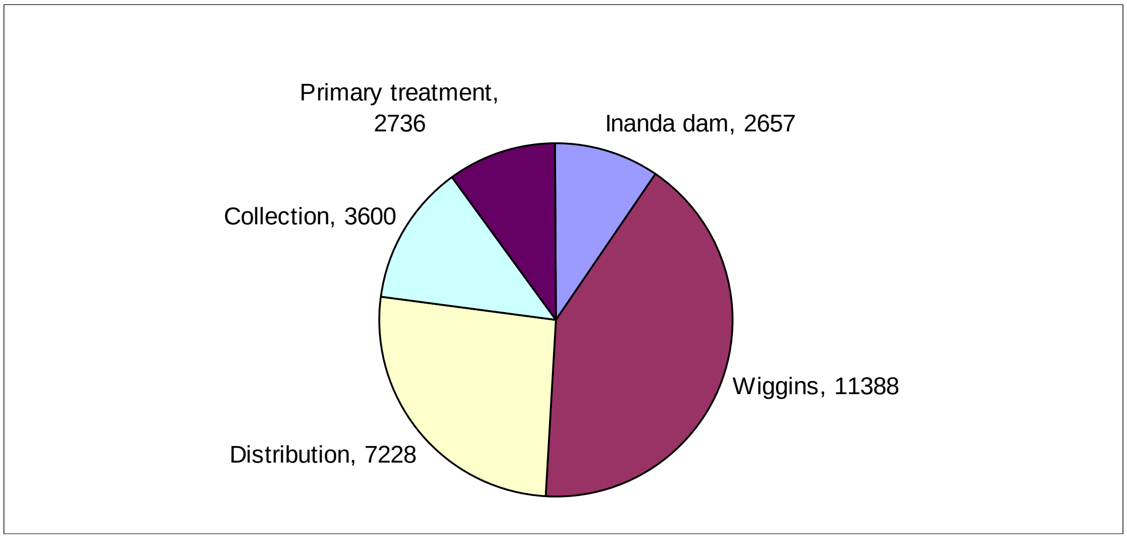

Figure 6-5: Global warming impact for the Base Case for the supply of water and sanitation services to 200 000 households per day (in kg CO_2 equivalents).

Table 6-2 shows how a total burden for the entire system was calculated.

Table 6-2: Breakdown of the global warming impact of providing 200 000 consumers in the eThekwini Municipality with water and sanitation using the units from the base case.

Unit	Vol produced (ML)	Impact per kL (kg)	Total Impact (kg)
Inanda dam	52	5.11E-02	2657
Wiggins waterworks	52	2.19E-01	11388
Distribution	52	1.39E-01	7228
Collection	24	1.50E-01	3600
Primary treatment	24	1.12E-01	2736
Total			**27609**

The sources of the impacts from the base case have already been examined in the interpretation and improvement analysis of Chapter 3. However it is important to ask whether the system as a whole is being managed efficiently and if not, could not an environmental improvement be achieved by better management practice.

At present approximately 30 percent of the 280 000 Ml purchased annually is unaccounted for within the ETM. Table 6-3 provides a detailed breakdown of the way water is used in the ETM. One of the important facts that the table shows is that 232 Ml / d of water are unaccounted. Of this 62 ML/d is from illegal connections and 170 ML/d from leaks. Because of this relatively high loss of water, a Non Revenue Water (NRW) branch has been established to reduce the amount of unaccounted for water.

Table 6-3: Breakdown of the supply and use of water within the eThekwini municipality (source Bailey, 2003)

Description	July 2002 to June 2003 (kl)	% of total
Amount of bulk water purchased (kl)	274901152	
Treated water supplied to:-		
Residential - full pressure water	104479534	54.99%
Residential - semi pressure	3497936	1.84%
Residential - groundtank / standpipe	4008635	2.11%
Non Domestic	77998590	41.06%
Others		
Subtotal treated water supplied	189984695	100.00%
Untreated water supplied		
Total water supplied	189984695	
Difference -> Purchase – Sales	84916457	31%
Reticulation leaks, Reservoir Overflows, Service connection leaks	62413596	74%
Illegal Connections	22502861	26%
Total water loss	84916457	

Consumers connected to illegal connections will be incorporated into the billing network of the municipality. This will not reduce the total water demand, however according the ETM's Integrated Development Plan (IDP) there is a 5 year goal of reducing the amount of illegal connections by 60%.

A reduction in water demand can be achieved by correcting the leaks. In 2003 the Inefficiency of Use (IOU) percentage was 30,4% and the Infrastructure Leakage Index (ILI) was 8.1. An ILI of 1 is equivalent to achieving the least possible water with regard to pressure, length of mains and number of connections. Plans are currently in place to lower the ILI to 5 in the medium term (IOU 25%) and in the long term an ILI of 3 (IOU 20%) should be achievable.

Some of the measures to be introduced are;

- Active Leakage Control -Leak detection is to be typically done in discrete areas where a base line has been obtained.

- Water Wizard - a GIS based utility, which enables monthly water balances to be carried out in areas where the bulk meters exist.

- High consumption customers are short-listed and contracted plumbers are instructed to investigate and leave an “offer to repair” letter. If consumption does not drop, the property is visited again after 3 months. If consumption does not drop and arrears are in excess of 60 d, a forced repair is done and charged to the consumer.

For large reticulation networks approximately 10% of water is lost through leaks which cannot be economically repaired (Bailey, 2003). A Swedish project investigating the environmental sustainability of urban systems stated that for a well functioning network a 15% leakage rate was acceptable (Lundin, 1999). If the ETMs measures are successful and even a 20% IOU is achieved an additional 150 Ml/d would be released for use by potential new customers.

Another way of increasing the available supply of water is to reduce the demand. This method called least cost planning (LCP) has emerged as the way forward for water utilities in regions where water conservation has become an objective or where ongoing supply expansion is constrained (Fane, 2004).

Least cost planning originated in the energy sector in the United States during the 1980s for comparing energy conservation programs to increased generation as sources of supply. It was based on the realisation that a kilowatt of electricity saved through demand management was the equivalent of an increased amount of supply (Beecher, 1996).

There are many ways of reducing the water demand in a large city and these fall into two broad categories. Consumer demand and supplier demand. In the case of Durban the eThekwini Municipality is the supplier and the inhabitants of Durban the consumers. Consumer demand can be reduced by using measures such as installing low flow showerheads, low flush toilets or by using legislation which introduces water restrictions such as preventing the watering of gardens during the day. Supplier demand can be reduced by identifying and reducing leakages in the reticulation network, removing illegal connections and reducing excess pressure across the distribution system to reduce leakages.

Bailey, in his study on using water supply tariffs as a water management tool, found that for the ETM, one of the easiest ways of reducing consumer demand would be to introduce a new tariff structure which would reward the use of less water and penalise heavy users of water.

Using Ramsey pricing principles a pro-poor tariff structure was designed for the ETM. This tariff structure ensures that the poor have access to affordable water services while the rich pay a premium to cross subsidise the consumption of the lower groups. In keeping with the national government policy, the first 6 kL per month of water is free to all households.

Bailey showed that by using this tariff structure an average reduction of 3.3 percent in consumer demand could be achieved. This is due to reductions in consumption from not only the high users of water but all users. Lower income users reduce their demand in order to stay below the 6 kL per month limit and thus not pay for water at all while middle and high income users reduce there demand to avoid being heavily penalised for using more than 27 kL per month.

The ETM currently supplies 753 Ml per day. A 3.3 percent reduction in demand would translate into almost 25 Ml per day being freed up for use by new customers.

Another benefit of demand management is a reduction in electrical use. Lundie (2002) found that by using demand management the energy requirement for a system could be reduced by 4% coupling this with energy efficiency measures could reduce the electricity demand by a further 9%. This would translate to a similar environmental benefit for this case due to the high electrical demand for the collection of sewage.

6.3. Option 1: Maximise the use of existing assets

This option involves using all the present units at their maximum capacity otherwise known as '*sweating the assets*'. When considering this option both scenarios are discussed as they share a common supply chain and differ only in the sanitation method.

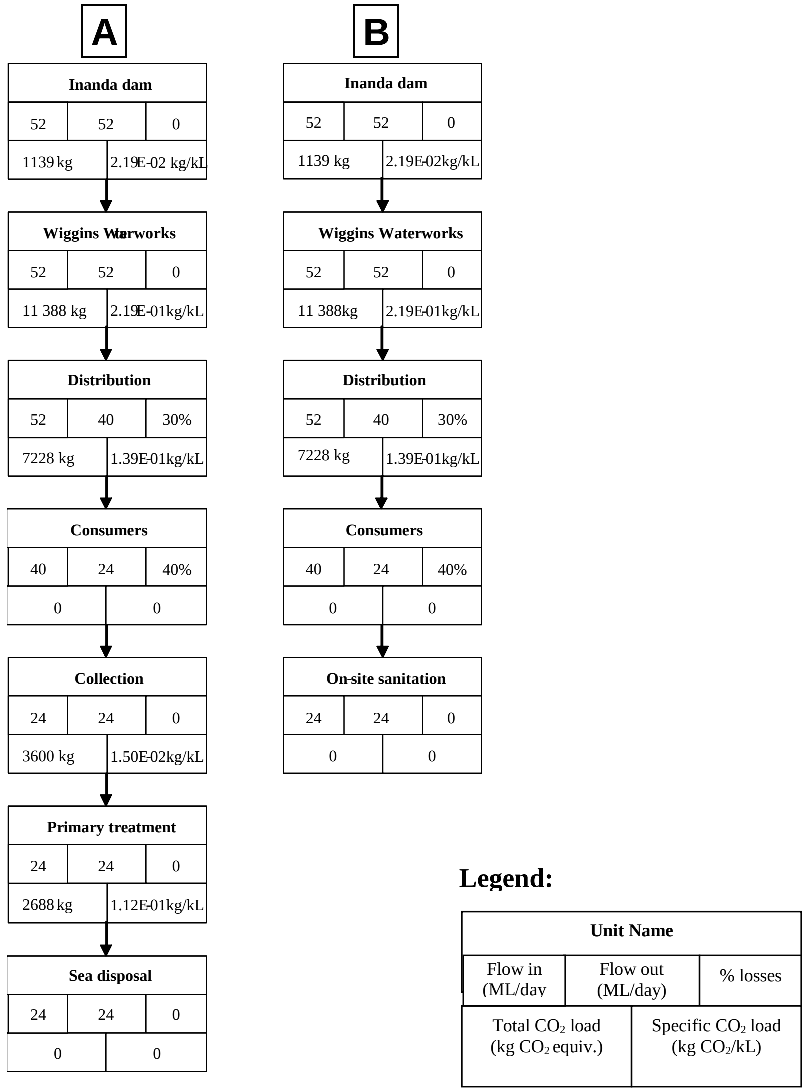

Figure 6-6: Simplified flowsheet of Option 1 (where the infrastructure is utilised to maximum capacity) for both scenarios

The environmental burden per kilolitre produced will change for some of the units and this will now be discussed.

6.3.1. Inanda Dam

Inanda Dam currently operates at production level of 200 ML/d. This could be increased to a sustainable 300 ML/d if necessary. The effect of this change would be to reduce the impact per kilolitre of water from 3.29E-02 kg CO_2 equivalents to 2.19E-02 kg CO_2 equivalents. Thus the total impact of providing an additional 52 ML/d is 1139 kg CO_2 equivalents per day.

6.3.2. Wiggins Waterworks

Wiggins is another unit that is operating at less than the design limits. Wiggins currently produces 170 Ml/d and has the capacity to produce 350 Ml/d. This increase would result in a proportional increase in the environmental burden. The total environmental burden for the global warming category is 11 388 kg CO_2 equivalents per day.

6.3.3. Distribution and collection

New networks would have to be constructed for the new customers. It was assumed that the specific energy for pumping would remain the same.

6.3.4. Primary Treatment

The primary treatment plant also has additional capacity available to treat the extra 24 ML/d that would be entering the plant. It was assumed that the specific energy for the treatment would remain the same.

6.3.5. Discussion

The total environmental impact of providing 200 000 thousand additional households with water and sanitation per day by maximising the use of the existing assets is presented in Table 6-4.

Table 6-4 Breakdown of the global warming impact of providing 200 000 new consumers in the eThekwini Municipality with water and sanitation by maximising the base case (Option 1).

			Scenario A	Scenario B
Unit	Vol produced (ML)	Impact per kL (kg)	Total impact (kg)	Total impact (kg)
Inanda dam	52	2.19E-02	1 139	1 139
Wiggins waterworks	52	2.19E-01	11 388	11 388
Distribution	52	1.39E-01	7 228	7 228
Collection	24	1.50E-01	3 600	0
Primary treatment	24	1.12E-01	2 688	0
Total			**26 043**	**19 755**

As anticipated, the burden attributable to option 1 is lower than the base case mainly due to the lower impact per kiloliter of water produced from Inanda dam.

6.4. Option 2 – Recycle water

This is the current scenario in the eThekwini Municipality. The scenario was chosen for number of reasons of which the most important were; the sea outfall was rapidly reaching its maximum capacity, there was a rise in demand from industrial consumers and it made good financial sense. Whether this was the best option environmentally for increasing Durban's water supply was not stated. Figure 6-7 shows this case.

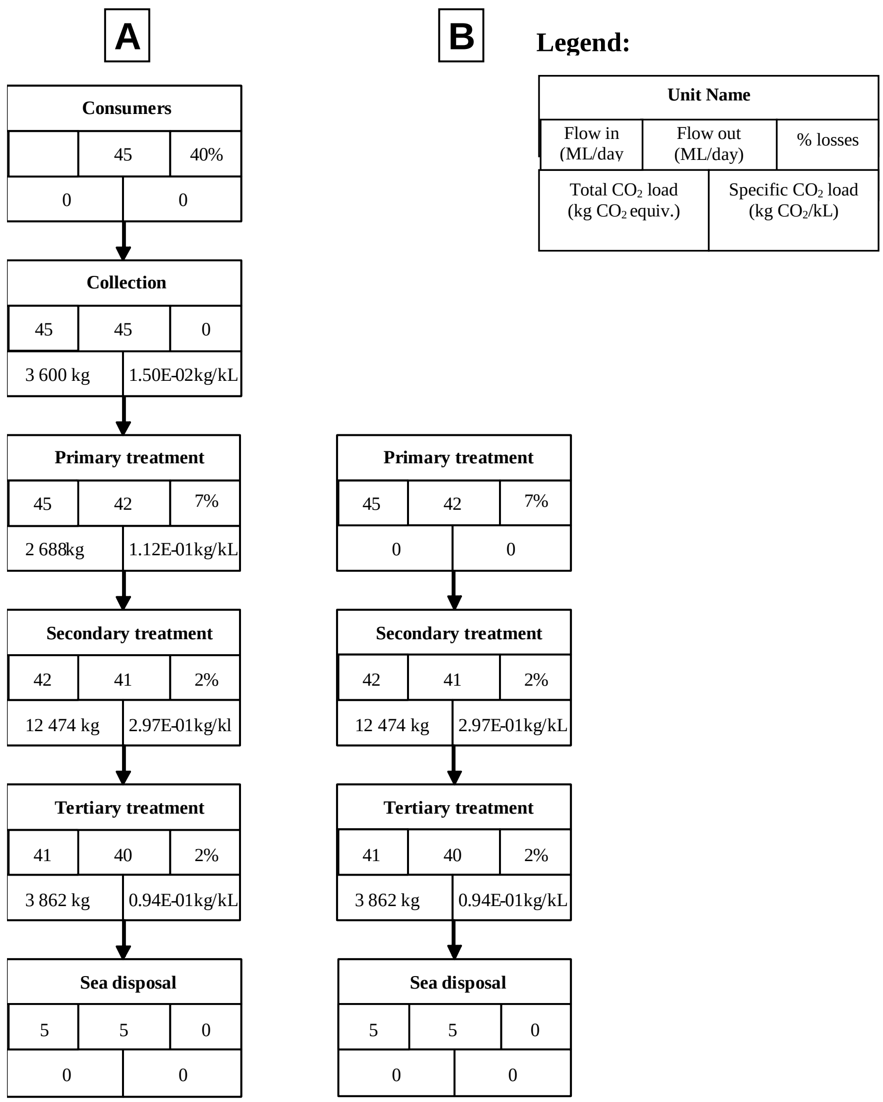

Figure 6-7: Simplified flowsheet of the Option 2 (the recycling case) for both scenarios.

The impacts of each unit were calculated in Chapter 3 and are now presented again in Table 6-5. There is a discrepancy in the outflow from the collection and the inflow to the primary treatment. This is due to the fact that one needs to recycle more than the wastewater of 200 000 households (24 Ml/d) to produce 40 Ml/d. This is made up by the domestic waste of other households in the ETM. When calculating the burdens attributable to the recycling plant it is important that they are allocated properly. One must bear in mind that the functional unit is the provision of water and sanitation services to 200 000 new households. Thus by using the recycling plant to supply industrial users and therefore freeing up potable supplies the households are responsible only for the environmental impact of the recycling plant and not the waterworks. Therefore the units leading up to the delivery of water to customers is given a zero environmental score. The new households still are responsible for the burdens of the primary treatment (those that have waterborne sewage).

6.4.1. Discussion

The total environmental impact of providing 200 000 additional households with water and sanitation by using recycled water is presented in Table 6-5.

Table 6-5: Global warming impact of Option 2

			Scenario A	**Scenario B**
Unit	Vol produced (ML)	Impact per kL (kg)	Total impact (kg)	Total impact (kg)
Collection	24	1.50E-01	3 600	0
Primary treatment	24	1.12E-01	2 688	0
Secondary treatment	42	2.97E-01	12 474	12 474
Tertiary treatment	41	9.42E-02	3 862	3 862
Total			**22 624**	**16 336**

By comparing the total global warming potential in Table 6-5 and Table 6-2 it is seen that Option 2 has a lower global warming impact than that of the base case thereby proving the case for introducing recycling schemes, since even though a lower quality of water is treated the environmental burden is still lower than the base case.

6.5. Option 3: Construct new infrastructure

The last option considered was one where to meet increasing demand, new infrastructure is constructed. When modelling this option it was taken that the best available technology would be used. The eThekwini Municipality has defined a *waterborne edge* around the core of the municipality, beyond this edge on-site sanitation must be provided. The method of choice is the urine diversion toilet as has been discussed earlier.

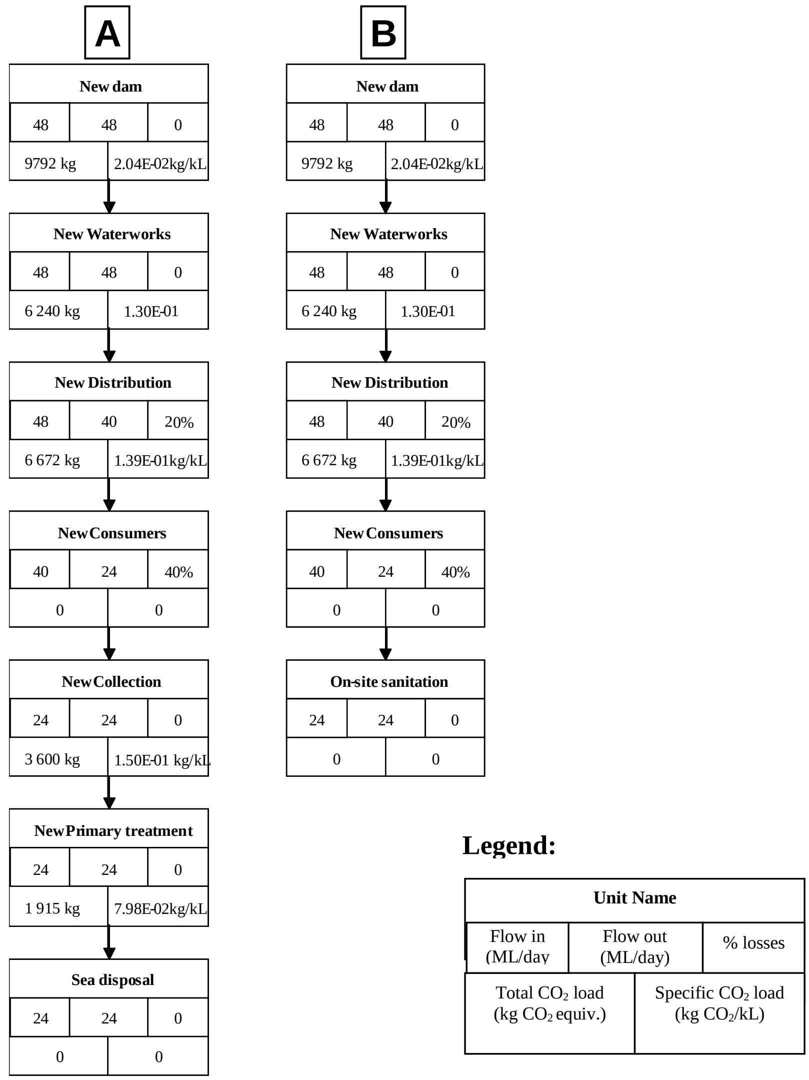

Figure 6-8: Simplified flowsheet for option 3 (the new infrastructure case) for both scenarios.

6.5.1. Dam

The environmental burden for the new dam would increase per kilolitre. It was assumed that at the start of operations only 50 Ml/d would be abstracted from the new dam. This would result in a global warming burden of 2.04E-01 kg/kl CO_2 equivalents.

6.5.2. Waterworks

There are no plans to build new waterworks to supply the Durban region. There have been no major technological advances that have dramatically reduced the environmental loads of large scale water treatment plants. Usually the reduction in environmental burden comes from the new plants being energy efficient.

Thus using Wiggins as a base case, it was assumed that a new plant would incorporate the same treatment units but be energy efficient. Currently the ozone process at Wiggins uses 4341.4 kWh/d (34 %) of a total of 12 612.9 kWh/d. It was shown in the improvement analysis section that this figure could be reduced by up to 80 %. This would reduce the electricity consumption of Wiggins to 9139.8 kWh/d. An improvement of 27%.

The recycling plant is essentially a water treatment plant employing all the same units as Wiggins Waterworks. It is a state–of-the-art design employing all the latest energy efficient technology. The global warming burden of the recycling plant is 1.01E-01 kg CO_2 equivalents per kL water produced. The global warming burden of Wiggins is 1.85E-01 kg CO_2 equivalents per kL water produced. Thus the recycling plant is able to treat a lower quality influent to an almost equal standard at a 45% reduction in the global warming load.

It was thus assumed that using energy efficient measures and even using the same technology a minimum environmental improvement (in the global warming category) of 30% could be achieved for a new water treatment works. This would translate to a global warming load of 1.30E-01 kg CO_2 equivalents per kL water produced.

6.5.3. Distribution

By using the measures discussed in Section 6.2 a reduction in the leak rate could be achieved. The aim of EWS is a leak rate of 20% and this was the rate that was assumed when considering the new infrastructure case.

6.5.4. Primary and Secondary Treatment

In Durban, the municipality has set a boundary outside which it will not provide waterborne services as it cannot afford to build and maintain a system to serve dispersed communities. In these areas Durban is increasingly promoting the use of a double alternating pit urine diversion (UD) toilet.

6.5.5. Discussion

The total environmental impact of providing 200 000 additional consumers with water and sanitation by constructing new infrastructure is presented in Table 6-6.

Table 6-6: Breakdown of the global warming impact of providing 200 000 new consumers in the eThekwini Municipality with water and sanitation by using Option 3.

			Scenario A	Scenario B
Unit	Vol produced (ML)	Impact per kL (kg)	Total impact (kg)	Total impact (kg)
New dam	48	2.04E-01	9 792	9 792
New waterworks	48	1.30E-01	6 240	6 240
Distribution	48	1.39E-01	6 672	6 672
Collection	24	1.50E-01	3 600	0
New primary treatment	24	7.98E-02	1 915	0
Total			**28 219**	**22 704**

6.6. Discussion

In any type of scenario analysis it is customary to rank the scenarios once the analysis has been performed. A simple ranking however would exclude the further possibilities that this scenario analysis has highlighted. Figure 6-10 traces where the source of the greenhouse gas emissions in each scenario are from. In Figure 6-9 the total global warming burden of each scenario is presented.

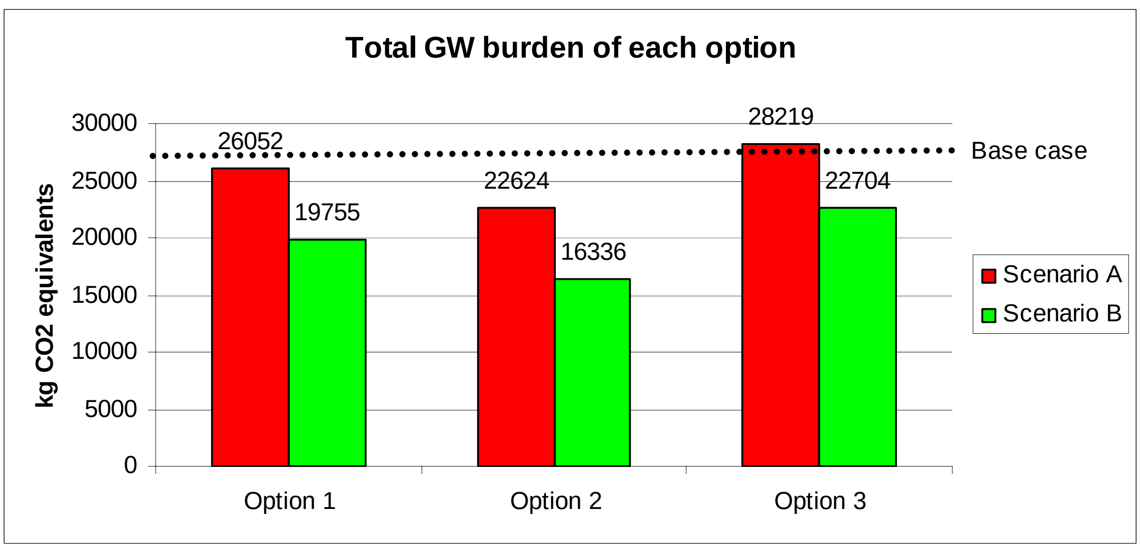

Figure 6-9: The total global warming burden of each option to provide 200 000 people with water and sanitation for each day.

Examining Figure 6-9 it is clear that for both scenarios A and B, Option 2, the recycling option is the best. Option 2 has already been implemented in the eThekwini Municipality and the results are based on operational data. The results clearly show that the addition of the recycling plant has reduced the environmental impact of water and sanitation provision. All the options have a lower environmental burden than the base case with the exception of Scenario A for the new infrastructure option. An important aspect that the study highlighted in the investigation of Option 3 is the importance of proper planning when constructing a dam. Dams should only be constructed if there is sufficient demand for the water that they can supply otherwise they act as greenhouse emitters for no return. Thus one should always aim to use a dam to its maximum capacity to get the greatest return for the environmental damage being caused.

The idea of using an asset to its maximum to get a lower environmental burden does not apply to sub-systems where the energy input increases in proportion to the volume treated (e.g. the waterworks)

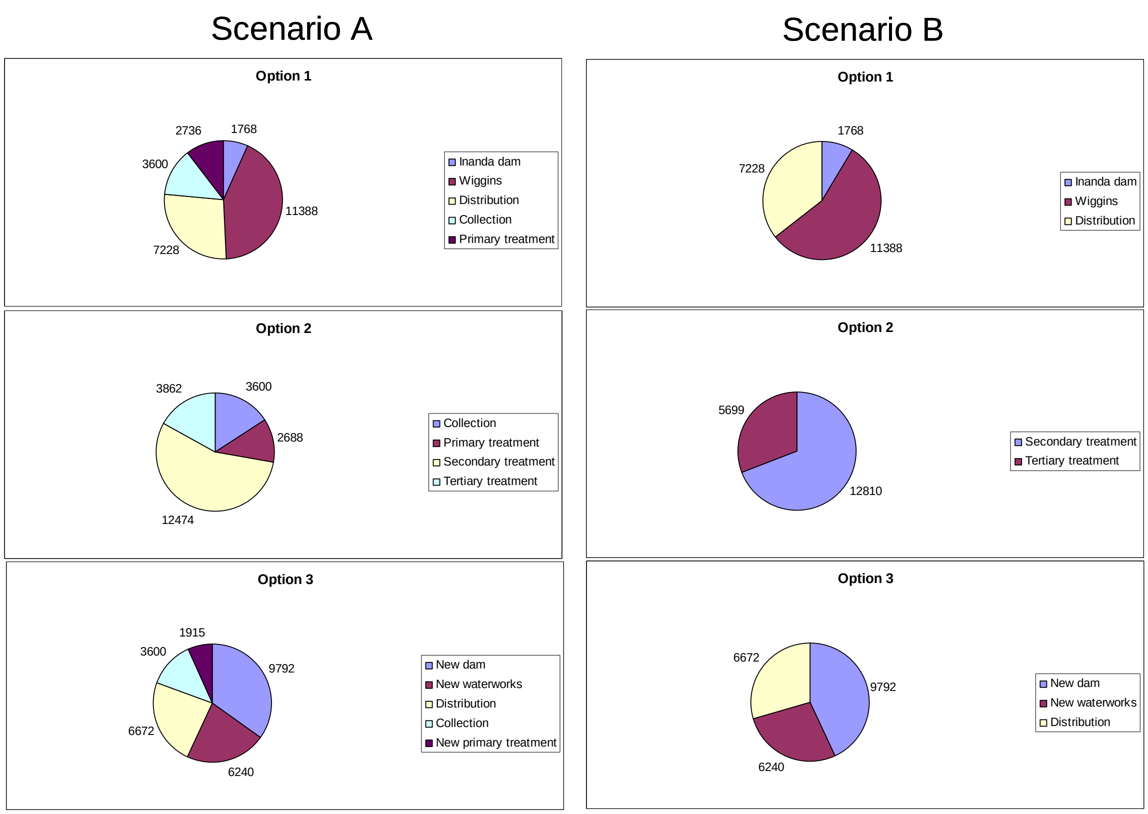

Figure 6-10: Comparison of the contributions of each sub-system to the global warming scores of each scenario. (kg carbon dioxide equivalents shown)

The question that now must be asked is, for a municipality looking to increase its available water and sanitation, what is the best route? Should one go straight to recycling, like Durban or are there better ways (environmentally) of doing so?

There are many variables to be considered when answering this question, the most important being;

- *The sanitation solution for new customers.* Since the impact of waterborne sanitation is the largest contributor to the environmental burdens this should only be used when on-site treatment cannot be used.
- *The location of the new customers*. On-site sanitation can only be used in rural and peri-urban areas. If the new customers are in densely populated urban areas then waterborne sanitation is the only option
- *The capacity of current infrastructure.* Is the infrastructure being used to its maximum capacity, is there room for expansion?
- *The quality of water required by the new customers.* Are they industrial or domestic users? If industrial, then what is the water used for and what quality required? Is potable water really necessary? How far are the industrial users from a wastewater treatment works?
- *The catchment capacity of the municipality*. In the event of new infrastructure being required is it possible to abstract more water through the construction of a new dam or must other options be considered?

The case of the three hypothetical municipalities

In order to examine the possibilities for increasing the available water and sanitation, and their associated environmental burdens, three hypothetical municipalities were considered.

Municipality 1: Mixture of dense urban, peri-urban and rural settlements. Treatment infrastructure not being used to the maximum capacity. The new customers will be a mix of industrial and domestic users. There is additional abstraction capacity in the catchment area. This is typical of the situation in large coastal municipality like eThekwini.

Municipality 2: Mixture of dense urban, peri-urban and rural settlements. Treatment infrastructure is operating to maximum capacity. Additional abstraction capacity available. Marine discharge of sludge is possible. Consider Cape Town as an example.

Municipality 3: Dense urban settlements. Treatment infrastructure used to maximum capacity. No additional capacity available. Not many central large industries. Inland sludge disposal. Johannesburg as an example.

The first two steps to increasing the water and sanitation capacity of a system are common to all municipalities and should be implemented even in municipalities who are not facing a water shortage. These steps are;

1. *General first step:* In any system, the first step is to ensure the system is running efficiently. This entails a program where losses in the system are identified and reduced The same efficiency measures must be practiced throughout the system and a thorough improvement analysis carried out as that in Chapter 3
2. *General second step:* Institute a water demand management program. This promotes cost savings and environmental saving thus creating a win-win situation. This is an easy and environmentally friendly way of immediately increasing a municipality's water supply.

Now for each case;

Municipality 1

1. *General first step*
2. *General second step*
3. What must be avoided is using a dam as a facility tank as this results in all the negative environmental effects for no return. Thus any dams in the system must be utilised at their maximum capacity.
4. As the largest burden accrues from the treatment of wastewater where possible residents should use on-site sanitation. This is the single most effective way of reducing the environmental load of a system.
5. Once the system is running at its maximum capacity a water recycling system should be instituted. The water recycling should take place preferably close to large industrial

customers who can accept a lower quality of water as the environmental burden of getting recycled water up to a standard for human use could be high. An important conclusion that is applicable to this analysis is that, *if there is no need to use potable water then don't supply it.*

6. Construct new infrastructure. This must be done using environmentally friendly processes. In the absence of a detailed LCA for a process the following rule of thumb can be used 'in general, the less electricity a process uses, the more environmentally friendly it is'

Municipality 2

1. *General first step*
2. *General second step*
3. For the peri-urban and rural residents an immediate introduction of on-site sanitation.
4. Water recycling for industrial users, thus freeing up capacity for domestic users. Again applying the principle of only supplying the minimum quality that is required.
5. Construct new infrastructure using environmentally friendly processes. In a municipality such as Cape Town where the is very little additional water available for abstraction alternative methods of producing water will have to be investigated such as desalination.

Municipality 3

1. *General first step*
2. *General second step*
3. Since it is not possible to introduce on site sanitation the municipality must ensure that the sewage treatment is operating efficiently with respect to electricity consumption.
4. Depending on the quality of the wastewater it might be necessary to use recycled water for potable use. Here energy efficient technologies should be used such as membrane filtration (Friedrich, 2000).

5. New infrastructure. In the case of a municipality with no additional abstraction capacity available this usually means pumping water from another catchment. This is usually done at a large electricity cost and thus a large environmental burden and therefore this option should be used as a *last resort measure*

In general for a South African city seeking to improve its environmental performance and become a more sustainable city there are three ways of achieving this;

- By incremental or continual improvement; while this option may deliver substantial progress in the early stages by capitalising on small easy improvements, international experience has shown that marginal improvements become smaller and hence more costly through time. An example of this is leak detection. Initially the savings will be great but will gradually taper off.
- By redesigning product, product lines or the services being delivered; this approach leads to an organisation to change actual products, processes or services to bring them in line with sustainability principles. Because redesign allows changes to be made earlier in the product cycle, the savings from increased resource productivity are often significantly greater than in the incremental approach. An example of this is the urine diversion toilet. It is an innovative solution to the city's waste problem and greatly reduces the environmental burden of the city.
- By rethinking the way in which people obtain value from the products or services themselves; this is a more radical change and involves a complete reassessment of how an organisation generates value. Changing the business model may imply a shift in patterns of both production and consumption as an organisation moves from a 'product based' orientation to a service business model – seen as a flow of services rather than a flow of goods. An example of this is the provision of industrial grade recycled water. Instead of just providing water the question that was asked was what service does the customer require? In this instance it was water for boilers and paper making. Hence there was no need to treat water to a potable standard when recycled sewage could be used.

For a city to improve its environmental performance and become more sustainable, all three approaches must be used concurrently.

6.6.1. Sustainability framework

The definitions of sustainable development are abstract and can be interpreted differently by different people. Critiques say that the term sustainability could mean almost anything. Some say that sustainability could become a plastic word; an ambivalent cliché of which everyone approves, but in the universal approbation people will agree on nothing (Mitcham, 1995). One of the most widely accepted definitions of sustainable development is the Brundland definition, this is, *development which meets the needs of the present generation without compromising the ability of future generations to meet their own needs* (WCED, 1987). This is the definition which was used for this dissertation as it aptly captures the problem facing municipalities ie to meet the needs (water supply and sanitation) of the present generation without compromising the ability of future generations to meet their own needs.

The results of the scenario analyses have facilitated the development of a sustainability framework for municipalities seeking to increase their water and sanitation. As stated in the introduction this is one of the key aims of this thesis. Currently the decision making framework (Figure 1-1) for municipalities only includes three focus areas; water resource, water demand and affordability, sustainable development is not taken into account. A fourth sustainability focus area is the outcome of this chapter. This focus area is meant to be viewed in conjunction with the existing focus areas. The framework is presented in Figure 6-11.

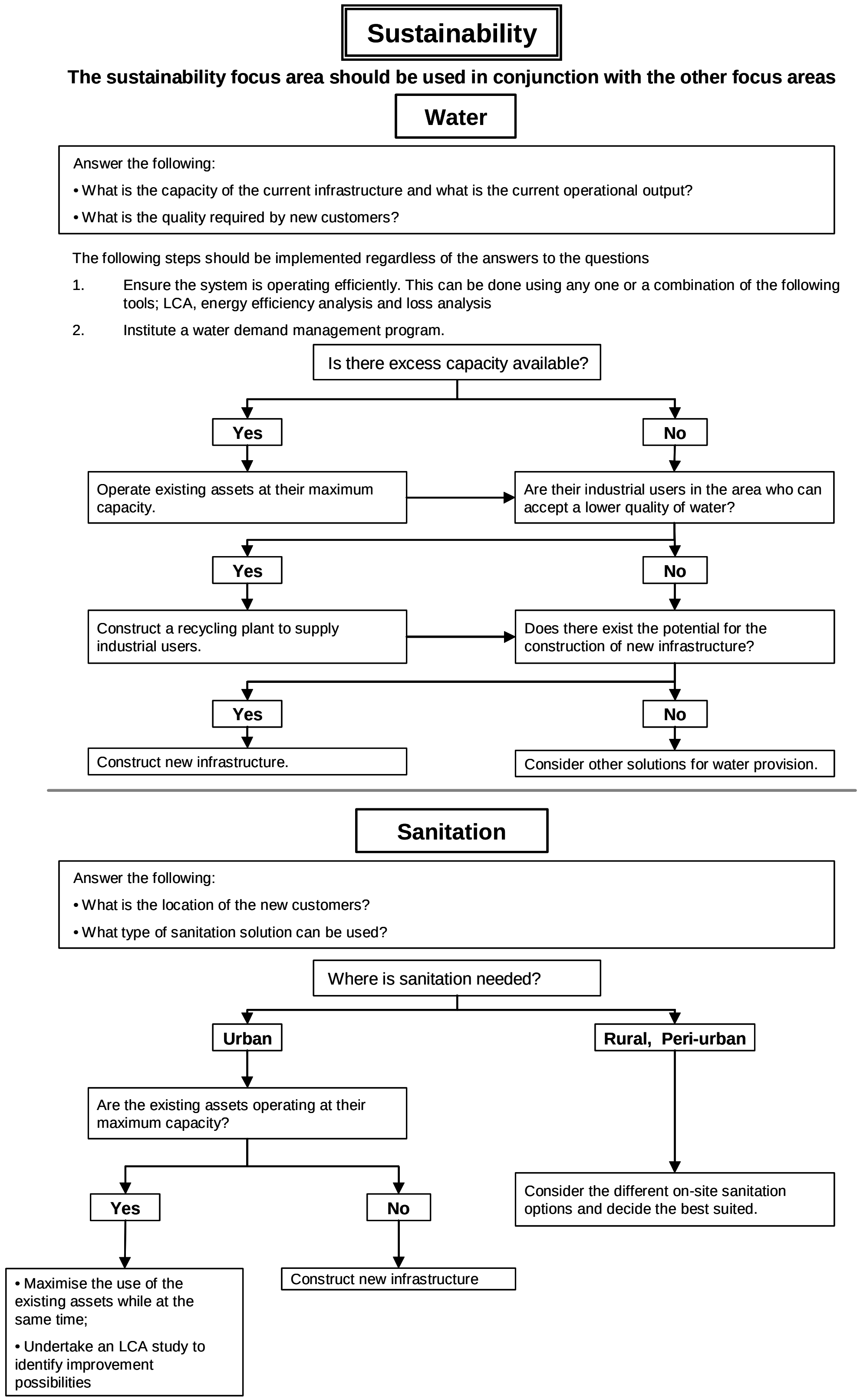

Figure 6-11: Sustainability framework for use with the Appropriate Solutions for Water Supply and Sanitation Framework

There are two separate decision frameworks presented in Figure 6-11 one for water and one for sanitation. Some recommendations from this framework stand out and are worth highlighting;

- In all cases the construction of a recycling plant is recommended,
- An efficiency analysis and water demand management program is mandatory,
- In the case of rural and peri-urban customers, on-site sanitation solutions are recommended.

The sustainability framework, developed here, is meant to be used in conjunction with the existing Department of Water Affairs and Forestry framework titled *Appropriate Solutions for Water Supply and Sanitation.* A sustainability assessment usually involves multi-dimensional criteria, including economic, environmental, social and technical aspects. The existing framework already makes provision for the consideration of economic aspects. This addition to the framework caters for the consideration of environmental and social aspects.

6.6.2. Additional options and scenarios

There are a number of additional scenarios that can be considered which make minor changes to the four detailed scenarios considered in this chapter. A qualitative analysis of these scenarios is now presented.

- *The effect of sending untreated effluent directly to sea.* This will lower the overall environmental burden of the system for the global warming category but might increase the burdens in other impact categories such as toxicity and eutrophication potential.

- *The trade off between using activated sludge to reduce COD as opposed to granular activated carbon and ozonation.* Currently the surface aeration methodology is not the most efficient way. Mels et al. (1999) showed that by introducing a pre-treatment step the energy requirements of the activated sludge could be dramatically reduced. Two pre-treatment options were considered. The first (Scenario A) used the addition of coagulant and flocculent followed by a pre-precipitation step. The second (Scenario B) used the addition of coagulant and flocculent followed by a flotation step. The reference system had exactly the same set up as the one in this study although the entering effluent had a lower BOD. It was found that the electricity usage could be reduced from 3100 MWh/year to 50 MWh/year for Scenario A and 300 MWh/year for Scenario B. For a South African treatment system this option is not used as the cost of chemicals outweighs the electrical savings. However the environmental improvements are potentially large.

- *Sludge treatment scenarios.* Further research is needed to examine means of sludge disposal in the South African context. This is particularly applicable to inland municipalities which do not have the option of discharging wastewater to sea. Matsuhashi et al (1997) carried out a comparative LCA of different sludge treatment options. Methods of disposal considered included landfilling, incineration and composting. The study also considered using the sludge as a resource. One conclusion that the authors drew was that when the sludge is used as soil improvement the benefit is comparable to the production and use of chemical fertiliser. Neumayr (1997) carried out a study on six different sludge recycling strategies. The main impacts associated with sewage sludge treatment were found to be energy use, diesel used in transportation and direct emissions of ammonia from composting and dewatering. Another LCA study by Suh (2001) comparing five alternative sludge treatment processes showed that a combination of anaerobic digestion and agricultural land application was the most environmentally friendly way of disposing of the sludge.

- *Supplying bottled water for food and drinking use and an untreated supply for other use.* This method is currently used in some developing countries like Indonesia where untreated water is supplied from a nearby river to households and bottled water for drinking and food use purposes. A brief study was carried out using data available in the literature to ascertain the viability of this option. Figure 6-12 shows a flow diagram of this option.

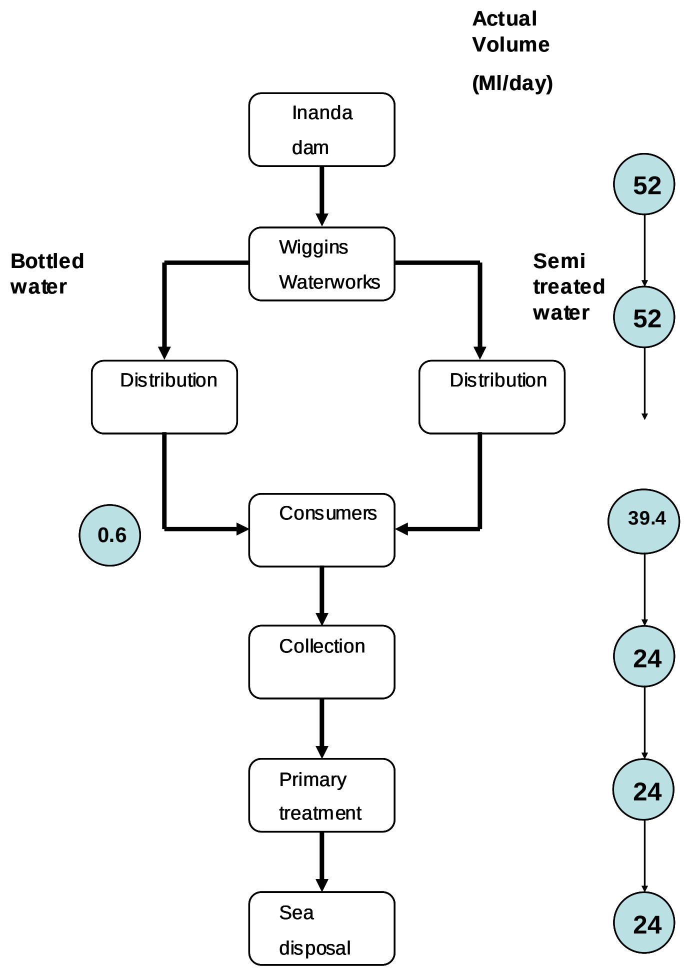

Figure 6-12: Simplified flowsheet of the bottled water option

Each person would be supplied with 3l/d of bottled water. The bottles are constructed from polyethylene terphthlate (PET) and can be washed and reused. For the purposes of this calculation the results of a Danish study, titled *Life cycle assessment of packaging systems for beer and soft drinks* (Ekval et al., 1998), was used. The study assumed that there would be a 98 percent recovery rate i.e. 50 uses per bottle. This study included the distribution of the filled bottles to the consumers in the calculation of the impacts. For the purposes of this analysis it was taken that the water to be bottled would be supplied by a conventional water treatment plant.

The semi treated water would undergo settling and filtration and the results from the impact assessment of the filters at the recycling plant were used for this calculation. Table 6-7 presents the global warming impacts of the bottled water option. Both scenarios were considered for this calculation.

Table 6-7: Summary of the impacts for the bottled water option.

			Scenario A	Scenario B
Process	Vol produced (ML)	Impact per kL (kg)	Total impact (kg)	Total impact (kg)
Production of water for bottling	0.6	7.03E+01	131	131
Production and distribution of bottles	0.6	2.19E-01	42 180	42 180
Production of semi treated water	51.4	9.01E-04	46	46
Distribution of semi treated water	51.4	1.39E-01	7 145	7 145
Collection	24	1.50E-01	3 600	0
Primary treatment	24	1.12E-01	2 688	0
Total			**55 790**	**49 502**

Over 75% of the global warming impact can be attributed to the production and distribution of the plastic bottles.

The results show the environmental impracticality of supplying bottled water due to the large burden accruing from the production of the bottles. The global warming burden of the bottled water option is more than double that of any of the other options for increasing the water supply for both scenarios. Although the treatment of potable water is a large proportion of the overall system impacts (42 percent) in the base case, as shown in the case studies of Options 1 through 3 there are better ways of mitigating this burden than using bottled water. Thus it would be more beneficial, environmentally, to treat the entire water supply to potable water standard than to supply bottled water for drinking.

6.6.3. Benefits and drawbacks of using LCA for evaluating urban water systems

The application of LCA for evaluating the environmental impacts of urban water systems has been criticised by Anderson (1998) for the fact that the existing technical system is often used as a starting point. Therefore there is a risk that possibilities or environmental problems are overlooked and only small improvements can be achieved which might delay the development of more sustainable technology.

This chapter addresses this problem by considering a wide range of possible scenarios which not only include modifying the present system but future infrastructure developments as well.

Another criticism of life cycle impact assessment (LCIA) in this context was made by Lundin (1999) who stated that LCIA needs to be expanded to include relevant environment interventions as the use of water is not included in any of the common weighting methods. This issue is addressed by looking at the potential water savings of an intervention as a positive environmental benefit. For example the score of producing potable water is reduced by recycling water.

Another criticism of LCA is that it does not adequately address qualitative aspects such as ecosystem health or sludge quality. This criticism is valid and where relevant the impacts that are not covered by LCA are presented in order to create a holistic picture.

One major advantage that this study has is that all the sub-systems where studied using the same methodology. Often it is hard to compare different LCA studies as different assumptions are made or different impact models used.

Balkema (1998) suggested a number of alternate impact categories when evaluating a technological improvement to a water or wastewater system. Some of these are;

- Economic affordability
- Construction, operation and maintenance requirements
- Adaptability to social, cultural and institutional environment

These are particular useful when introducing a new technology such as the UD toilet to a community. In different cultures, people have a different perception of waste and sanitation resulting in different habits. Some people view waterborne sewage as the only sanitary disposal option and they cannot be convinced otherwise, then this technology would not be appropriate. The need to explain to visitors how to use a separation toilet was one of the reasons to remove these toilets from the houses of an ecological village (Fittschen, 1997). In this chapter the LCA study was conducted on a supposedly socially and financially acceptable base of options.

6.7. Conclusions

It has been estimated by the Department of Water Affairs and Forestry that the demand for water may exceed the available supply in the next ten years. Therefore there will be a point where it will not be possible to construct new infrastructure to abstract and treat water. Instead the methods suggested to reduce water demand and the recycling of water will have to be considered. This chapter has investigated different scenarios and options for increasing the provision of water and sanitation services in a sustainable manner.

For the studied system the emissions need to be put into perspective. For the system studied these are in the order of 7000 t/annum for the emissions of greenhouse gases. This is for the provision of water and sanitation for 200 000 consumers. If one extrapolates this for the approximately 35 million South Africans who have access to free basic water and sanitation then this figure is 1 225 000 t/annum. This figure is small when compared to the estimated 300 million tons per annum of GHGs that South Africa emits. However one must remember that South Africa is one of the top twenty GHG emitting nations in the world and this figure is unnaturally high for an economy of our size. This is due largely to the fact that SA is almost completely dependent on coal based power generation which accounts for 80 percent of these emissions. Therefore it is critical that all new developments are made taken into account the sustainability principles presented in this chapter.

In the book Sustainable Technology Development (2000), Weaver predicts what the municipal water chain will look like in 2040;

The water chain in 2040 is characterised on the supply side by a cascade of functions, with the quality of water finely tuned to the function. Wastewater from one function that is suitable for another (lower) function is cascaded down the function hierarchy. The waste system is no longer used as a disposal and transport system for waste materials that are not intrinsic to the wastewater system. Wherever possible, waste materials are held in solid form and are not put into the water system at all. When it is still necessary for wastes to enter the water system, as little water as possible is used to carry the waste away since this minimises the subsequent task of separation and treatment of the water and the solid wastes so that these can be re-used.

Already we are starting to see some of these ideas in new water recycling schemes. By using the LCA tool one can quantify the environmental cost or the environmental saving gained when one is faced with a number of options as was shown in this chapter.

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Chapter 7 : Conclusions and Recommendations

7.1. Conclusions

This chapter summarises the main findings of this study and presents the recommendations for future research. The limitations and errors are also discussed. Sustainable development is the overarching concept of this study. This concept aims to re-direct development onto a path in which industrial expansion and advancement are done in such a way so as to protect humans and the environment. Cleaner production is one way of striving for a more sustainable path for industry and business. Cleaner production is based on the principle more with less and it promotes the increase of overall efficiency and the reduction of risks to people and the environment by the continuous application of a preventive environmental strategy to industrial and business activities in general. There are a number of tools employed in cleaner production and LCA is one of them. LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, service or activity over its entire life cycle (i.e. from cradle-to-grave). It takes into account releases to all media (water, soil and air) and the consumption of raw materials. This tool has definite advantages, most notably its holistic quantitative and comparative approach from a cradle-to-grave perspective. It also detects the shifting of pollution between media or processes. In the last decade a series of applications emerged for LCA in the water industry and this research is such an application.

The overall objective of this study was to generate information on the environmental life cycle of water in an urban context. This included the abstraction and treatment of raw water, the distribution of potable water, the collection and treatment of wastewater, the disposal to sea of effluents and the recycling of water. Of particular interest was the environmental efficiency of recycling water for industrial use and to examine the net effect of recycling.

7.1.1. The main findings of the study

The LCA impact analysis in Chapter 3 of each individual unit provided some valuable insights into where the major environmental impacts lie in a water and sanitation system. By breaking up the system into sub-systems and then further analysing these subsystems as individual processes one could easily identify the units which could be targeted for environmental improvement. By studying the construction, operation and decommissioning phase of each sub-system separately we were able to confirm the literature findings that the operations phase was responsible for the majority of the impacts.

The results showed that the operations phase was responsible for over 90 percent of the environmental load for all the studied impact categories. This result is in line with many other LCA studies on water and wastewater treatment processes (Emmerson et al., 1995, Meijers et al., 1998, Grabski et al., 1996). This lead to a streamlining of the study and for some of the units, detailed calculations to assess the environmental impact of the construction and decommissioning phase were not carried out. This resulted in a large time saving without a significant loss in accuracy.

One of the unexpected findings was the low environmental impact of the dam for the LCA categories. Although the dam is a major emitter of greenhouse gases, per kilolitre however, the impact of the dam are small compared to the other treatment processes. Most of the impacts occur during the construction stage, many of which are not encompassed by traditional LCA impact assessment methodology. The impact analysis of the dam was completed by undertaking a social analysis. This was necessary as in some cases, the social impact of dam construction outweighs the environmental impacts.

A closer examination of the operations phase revealed that with the exception of the human ecotoxicity category, the use of electricity resulted in almost 80 percent of the burdens of the other impact categories. It must be noted that this is specific to water and wastewater treatment processes, where the chemical input is small in comparison to the electrical input. This resulted in the development of an electricity index as a performance indicator. *This is one of the major outcomes of this thesis as it allows for a simple measurement of environmental performance by monitoring electricity consumption*.

The results from the LCAs of each unit in Chapter 3 directed the study to two areas; how to minimise the electricity use of the system and secondly to examine more closely the generation of electricity in South Africa and the impact model used.

With regard to the first, the two highest electricity using processes were targeted for an improvement analysis. These were the activated sludge treatment process and the ozonation process at Wiggins Waterworks, which uses 9700 and 4300 kWh/ day respectively. These processes were analysed in detail in order to ascertain exactly where and how the electricity was being used. Different improvement measures were suggested and in some cases tested. The improvement analysis showed that the electricity use of the ozonators at Wiggins Waterworks could be reduced by as much as 80 % by limiting the air flow to the thermal destruct unit, used to destroy excess ozone.

A detailed analysis of the activated sludge unit was conducted. Various methods of reducing the electricity usage of the system were considered. These included; alternate aeration methods, varying the operating conditions and using a chemical pre-treatment step. The possibilities for reducing the electricity consumption for this unit are large with the possibility of an order of magnitude reduction. However due to the sensitive nature of the process trials were not able to be carried out. It must be stated that electricity efficiency measures are not a priority in the South African water industry due to the relatively low cost of electricity. Rather the focus is on reducing the chemical consumption which contributes to a large proportion of the operating expenses.

The social impacts of the provision of water and sanitation were investigated in order to create a more complete picture. The results from the social impact analysis differed from the environmental analysis in that the impact of the construction phase was found to be significant. The construction of Inanda Dam was shown to have the largest impact of any of the studied sub-systems due to the forced removal of the residents in the dam's floodplain. Another area, which is often neglected in social impact assessments, was the impact of electricity use during the operations phase. Here the advantage of using the LCA methodology is clear and the impact of electricity generation, although occurring hundreds of kilometres away, is included. The highly localised nature of the power stations result in a concentration of the pollution effects. An increase in respiratory illnesses in the area of the power stations has been noted. However no scientific studies have been carried out to validate these claims.

In Chapter 6 scenarios were considered to investigate how best the water and sanitation supply levels in the eThekwini Municipality could be increased. The results of the LCA study in chapter 3 provided a base case. The options investigated were, maximising the use of existing assets, water recycling and the construction of new infrastructure. In order to quantify the total impact of each option and thereafter rank them, a service based functional unit was chosen. The functional unit was the provision of a basic level of water and sanitation services to 200 000 new customers. The scenarios considered customers in both rural and urban areas. A number of interesting findings arose. These are summarised here;

- The first step for any municipality needing to expand its water and sanitation service levels is to examine how well the present infrastructure is being utilised. This includes a waste minimisation program, leak detection and a water demand management program. Existing assets should also be individually investigated to determine the potential scope for improvement.

- When seeking to reduce the environmental impact of a water and sanitation system an energy audit is preferable to a detailed LCA. This is quicker to perform and this study has shown that electricity is responsible for the majority of the environmental impacts. Friedrich and Pillay (2005) proposed the use of an electricity index as a measure of environmental performance for urban water systems in South Africa. The amount of energy expressed as kWh/kl of water (potable or wastewater) is enough to simplistically judge the overall environmental performance of existing water systems. It is also a relatively easy index to use from the point of view of the technical staff involved in operating water plants and pumping stations and which usually are not familiar with global warming and CO_2 equivalents. The use of an electricity index would be a good measure, as long as the underlying data (i.e. electricity consumption) can be measured reliably and assigned to different operations or processes

- Alternate methods of sewage treatment should be considered if possible. On-site treatment systems such as the urine diversion toilet being used by the eThekwini Municipality have a low environmental impact provided they are operated correctly. This is dependent on the location of new customers as on-site sanitation methods can only be used in rural or peri-urban areas.

- By using all existing assets at their maximum design capacity, a reduction in the total environmental burden can be achieved. Dams need to be operated at their design abstraction limits otherwise they act as large greenhouse gas emitters for no return. The use of the LCA technique resulted in a quantification of the environmental impacts from the dam.

- Although the recycling of water is energy intensive, it has a net positive environmental impact. It is important therefore, to ascertain the quality of water required by the customer. If only an industrial grade is required then only that should be supplied. This is not a blanket generalisation as was found when analysing the impact of providing bottled water. In that instance it was better to provide a potable water supply to all consumers than to separately provide bottled water for drinking purposes only. This was due mainly to the large burden associated with the production of the bottles.

One of the most important outcomes of this thesis is the development of a framework for the sustainable expansion of a water and sanitation system. This framework serves as an addition to the existing framework for 'Appropriate Solutions For Water Supply and Sanitation'. This addition allows decision makers to include sustainability criteria when considering expansion options.

7.1.2. Important limitations of these conclusions

While LCA is a valuable environmental tool it is not the right tool for evaluating all environmental impacts. For the analysis of the dam environmental impact assessment is probably a better tool as LCA neglects impacts such as changes in bio-diversity and downstream river morphological effects. For the other water and wastewater treatment process LCA provides a good representation of their environmental impact. The use of LCA in water treatment processes is well documented and its focussing ability is a valuable tool.

The use of a non South African database to calculate the magnitude of the impacts results in some inaccuracies. However for the important emissions from the generation of power these measurements are close enough to the GaBi database to be used.

7.2. Key questions revisited

What is the environmental and social cost of the provision of water and sanitation services in the eThekwini Municipality?

It was hypothesised that LCA was an appropriate tool to answer this question. Chapter 3 provided a quantification of the environmental cost of supplying 1kL of water and treating 1kL of wastewater for the individual unit while Chapter 6 examined the system as a whole. 8 impact categories were investigated. LCA provided a good description of the system's environmental burden. However, during the course of the study it was found that there were a number of impacts that existed outside these 8 categories. These impacts are mainly social impacts that occur during the construction phase of a project (e.g. Inanda Dam). These impacts are hard to quantify but were presented in order to provide a more complete picture.

The results of the LCA in Chapter 6 showed that in terms of South Africa's environmental total environmental profile, the contribution from water and sanitation is small (less than 1%). Therefore in the global .scheme of things water and sanitation should not be prioritised as being a sector with a large environmental burden and targeted for emissions reduction. However, with the current pressure on cities to ensure that their growth is sustainable it is important that future expansion to water and sanitation infrastructure be done in accordance with the sustainability framework developed in Chapter 6.

Regarding the social impacts, the social impact of not providing proper water and sanitation facilities is undoubtedly high and this was not considered by this study as it was taken as a given that water and sanitation services will be expanded. The impacts of the different sanitation methods were investigated. It was found that on-site sanitation methods had the lowest burden, however, this cannot be used in an urban environment. In an urban environment where sewer bourne sanitation is used it was revealed that the majority of the environmental burden could be traced to the activated sludge units due to the high electricity use. Therefore this unit should be the subject of an improvement analysis.

What are the main contributors to this?

The main contributions to the environmental impacts come from the use of electricity during the operations phase of each the system. For the social impacts the main impacts occur during the construction phase and in particular from the health impacts associated with the generation of electricity. This led to the development of an electricity index which can be used to measure environmental performance.

Are there ways of reducing this load and if so by how much?

An improvement analysis was carried out in Chapter 3 to see how the existing system could be improved. This analysis showed that large environmental savings (up to 80 percent for some sub-systems) could be achieved by making modifications which made the processes more energy efficient. Examples of some units that were targeted for improvement were the ozonation and activated sludge unit. In the case of the ozonation unit it was found that by limiting the airflow to the thermal destruct unit a 70% reduction in electricity usage could be achieved without compromising the performance of the unit.

The operating parameters of the activated sludge unit were investigated and the unit modelled to see the effect of changes. By optimising parameters such as sludge age, wastage rate, aeration levels and recycle rate it was shown how the environmental performance of the unit could be improved.

When examining the system as a whole in Chapter 6 two basic steps for improving the environmental performance were suggested. These are an efficiency analysis and a water demand management program.

How can the water and sanitation service levels be increased? What is the most environmentally friendly way of doing this?

If one had to rank the best way of increasing the water and sanitation levels in a municipality one would first implement a review of how the system is operated and then, if possible, try to maximise the use of existing assets. The second step would be the introduction of water recycling schemes. These schemes can be for the provision of industrial and potable grade water, however it should be noted that where possible the quality of supply should be tailored to the needs of the consumer. Finally the construction of new infrastructure should be considered.

In Chapter 6 a framework for municipalities expanding there provision of water and sanitation services was developed. This outlines how water and sanitation service levels can be increased in a sustainable manner.

What is the net effect of providing recycled water in Durban? Is this the best way of increasing the water supply? The results of the scenario analysis (Figure 6-9) show that it is clear that for both scenarios A and B (waterborne and onsite sanitation), Option 2, the recycling option is the best. Option 2 has already been implemented in the eThekwini Municipality and the results are based on operational data. The results prove that the addition of the recycling plant has reduced the environmental impact of water and sanitation provision in the eThekwini Municipality. An important aspect that the study highlighted in the investigation of Option 3 (new infrastructure option) is the importance of proper planning when constructing a dam. Dams should only be constructed if there is sufficient demand for the water that they can supply otherwise they act as greenhouse emitters for no return. Thus one should always aim to use a dam to its maximum capacity to get the greatest return for the environmental damage being caused.

The question of whether recycling water is socially acceptable is not relevant to this study as the recycled water is only utilised for industrial use and these users are mainly concerned with the price and quality of the water rather than the source. The social impacts of the provision of recycled water were analysed in Chapter 4. The analysis showed that overall recycling had a small impact when compared to the impacts associated with the construction of new infrastructure such as dams.

7.3. Recommendations

From the LCA scores calculated in Chapters 3 and 6 it is obvious that the use of electricity is the process which carries the highest environmental burdens for urban water systems. Therefore, most of the recommendations for environmental improvement focus on increasing the electricity efficiency of the systems. Firstly, accurate electricity measurements are necessary in order to assign electricity consumption to processes and/or pumping stations in the water system.

The LCA scores from this research suggest that as a simplistic measure on the environmental performance of urban water systems an electricity index be recommended. This index is the amount of electricity calculated per kilolitre of potable water or wastewater produced and/or moved in the system. A compilation of such indexes for South African urban areas would help benchmark and compare environmental performances. It will also highlight areas for improvement.

The majority of LCA studies of water and wastewater systems have compared different treatment methods. One of the important conclusions that these studies have in common is that in order to improve the sustainability of the systems, attention should focus on minimising the discharge to water and minimising sludge production (Lundin et al, 2000). This study does not focus on these impacts as the sludges are deemed to have a low environmental impact when disposed to sea (Carter, 2003). However this method of disposal is not sustainable and the current sea outfalls in the eThekwini Municipality are operating at close to their maximum capacity. The method of disposing sludges using the current deep sea outfall in Durban is considered unsustainable due to the fact that At the current loading the environmental impact is low, however there is little or no potential for expansion. An increase in the volume of sludge discharged on the current deep sea outfall would have a disproportionally high impact.

Further research is needed to examine means of sludge disposal in the South African context. Matsuhashi et al. (1997) carried out a comparative LCA of different sludge treatment options. Methods of disposal considered included landfilling, incineration and composting. The study also considered using the sludge as a resource. One conclusion that the authors drew was that when the sludge is used as soil improvement the benefit is comparable to the production and use of chemical fertiliser. Neumayr (1997) carried out a study on six different sludge recycling strategies. The main impacts associated with sewage sludge treatment were found to be energy use, diesel used in transportation and direct emissions of ammonia from composting and dewatering. Another LCA study by Suh (2002) comparing five alternative sludge treatment processes showed that a combination of anaerobic digestion and agricultural land application was the most environmentally friendly way of disposing of the sludge.

7.3.1. Recommendations for further research

A summarised list of recommendations follows;

- To explore the potential for reuse of nutrients from both the on-site and municipal treatment processes which exists.
- An LCI model for assessing the impact of electricity generation in South Africa needs to be created. Although it was found that the GaBi database did not differ significantly from the database prepared by Notten (2001), since electricity is such a large contributor to the environmental burdens, it would be valuable to have up to date, detailed electricity data available.
- The development of on-site sanitation methods.
- The development of low electricity load activated sludge processes.
- Alternate sludge disposal methods. Discharging sludges to sea is not sustainable and alternate disposal technologies need to be investigated.
- The development of a quantitavive LCA based algorithm for working out beyond which population density the trade-off between fossil energy investments and localised impacts make on-site sanitation the preferred method.

7.4. Concluding statement

The objectives of this research project have been achieved. The environmental profiles for the different stages in the urban water cycle have been calculated and they show the life cycle environmental consequences of the technologies/processes employed. Recycling of water proves to be the most environmentally friendly option, however, care should be taken with generalising this result. Recycling of water can only be done in areas where there are industrial customers who can accept this lower grade of water. This thesis did not examine the impacts of recycling wastewater to a potable standard. Electricity consumption is the process, which carries the highest environmental burdens for urban water systems, and environmental scores closely match electricity consumption. Therefore, this parameter can be used as a surrogate indicator for environmental performance in benchmarking urban water systems. When looking at urban water systems, water losses in the distribution system have to be taken into account. The use of LCA as an environmental impact focussing tool was demonstrated and solutions for improvement are presented. LCA also proved to be very useful with regard to the scenario analysis performed and proved to be an adequate tool for calculating the environmental impacts of a water and sanitation system.

When considering the social impacts, the LCA tool could not be used directly and an LCA type methodology was developed. This proved adequate for the studied system and succeeded in creating a more complete understanding of the studied system.

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Appendix 1 : Abstraction and Storage of Water

This Appendix investigates the abstraction of water from the environment and as a case study the Inanda Dam is presented. The appendix expands on the work presented in Chapters 2 and 3 in that a greater level of detail is presented. Inanda Dam is one of the two large dams supplying potable water to the eThekwini Municipality and the city of Durban. Only the environmental impacts of Inanda Dam are considered in this appendix.

1.1. Introduction

Inanda Dam has a concrete wall with an earth embankment design as shown in Figure 3.1. The dam is fed from a catchment area of 4 082 km^2. The total capacity of Inanda Dam is 251 746 x 106m^3 and the dam has a surface area of 14.63 km^2. The dam has an 'S' shape. Entering water has a residence time of approximately two years. The maximum daily abstraction capacity of the dam is 300 ML/d and the dam currently produces about 200 ML/d. The main river entering the dam is the Umgeni river, the dam is situated 32 km inland of the river mouth (Garland, 2000).

Inanda Dam was constructed in 1989 amid much controversy. This was a period during the apartheid era in South Africa and the situating of the dam in the midst of a tribal area in an 'independent' homeland was regarded with hostility by the local community. The way relocation of local communities proceeded was also a debated issue and caused social problems.

1.2. Literature Review

The literature review for this appendix covers the environmental impacts associated with dams (including a life cycle perspective on these impacts).

1.2.1. Environmental Impacts of Dams

As with any dam there are environmental impacts that result from a change in the hydrological regime of the river. Often these impacts are hard to quantify and lie outside the boundaries of the LCA impact categories. This section presents some of these impacts that apply to both Inanda dam and dams in general.

Garland (2000) studied the geomorphological impacts of Inanda Dam on the Mgeni estuary, north of Durban. He showed that the mean annual discharge of the Mgeni river was reduced by 4% following the construction of the dam. Retention of sediment behind the dam wall has led to a reduction in available downstream sediment resulting in a much finer sediment in the estuary. Another impact of this reduction in sediment discharge is the ultimate deepening of the estuary as residual pre-dam sediment is flushed through and not replaced by new material from upstream. Since Umgeni sediment is a source of material for natural beach nourishment, it is likely that beaches will become narrower. There have been no other detailed studies of the specific environmental impacts of Inanda Dam. The negative and positive environmental impacts that the Inanda dam development shares with most large dams have been summarised in the literature (World Commission on Dams Report, 2000) and are presented in the following paragraphs.

Negative Environmental Impacts

- The altering of a water course affects downstream ecosystems
- There is a reduction in organic and inorganic sediments on which freshwater ecosystems depend
- Disruption of fish and mammal migration patterns
- Reduction in downstream flooding may result in less natural submergence for flood-recession agriculture, reduction in groundwater recharge and reduction in removal of parasites by natural flooding
- Aquatic weeds (floating and submerged) may proliferate, especially in tropical areas: Water hyacinth and water lettuce
- Salination of floodplains
- Reservoirs can positively affect some fish species (and fisheries) by increasing the area of available aquatic habitat. However, the net impacts are often negative because (a) the dam blocks upriver fish migrations, while downriver passage through turbines or over spillways is often unsuccessful, (b) many river-adapted fish and other aquatic species cannot survive in reservoirs, (c) changes in downriver flow patterns adversely affect many species, and (d)

water quality deterioration in or below reservoirs (usually low oxygen levels; sometimes gas supersaturation) kills fish and damages aquatic habitats. Freshwater molluscs, crustaceans, and other benthic organisms are even more sensitive to these changes than most fish species, due to their limited mobility (Bergkamp, 2000).

- Potential dam failure, this can lead to catastrophic flooding.

Positive Environmental Benefits

- Reduced flooding: Reduced flooding downstream of dam due to flow regularity lessens erosion and damage to farmlands
- Tourism development: Programme to develop tourism in the area (fishing, canoeing, hiking trails, campsites etc.) and the potential for job creation related to tourism
- More controlled downstream water quality: Reduced sediment levels will improve the downstream water quality.

A survey of 87 dam projects by the World Commission on Dams found that the top five environmental impacts were; impedance of migratory fish, reduced water quality due to phosphates, reduced bioproductivity at the reservoir area, geomorphological changes down river and reduced bioproductivity down river (World Commission on Dams Report, 2000).

In addition to the positive and negative environmental impacts as presented above, an LCA will add more valuable information on the total environmental burden of a dam including construction and decommissioning, not only the operation.

1.2.2. Environmental Impacts – An LCA Approach

The life cycle of a dam consists of three stages: construction, operation and decommissioning. All these stages have different inputs and outputs contributing towards the total environmental burden of the dam. In the construction stage fossil fuel (diesel) is used by the earth-moving equipment and concrete and steel are used in the structures of the dam. Taking into account these inputs, LCA scores can be calculated for the construction of a dam. For the operation stage, however, the inputs and outputs are significant for only one impact category, namely global warming. It has been discovered that important amounts of greenhouse gases (carbon dioxide and methane) are emitted from dams (Louis et al., 2000). These gases are produced by aerobic (carbon dioxide) and anaerobic (carbon dioxide and methane) decomposition. Louis (2000) and his team at the University of Alberta estimated that reservoirs worldwide release 70 million tons of methane and around a billion tons of carbon dioxide annually. Reservoir releases of the two gases combined contribute to an estimated seven percent of the global warming impact of other human activities calculated over a 100 year period.

For warm climates it is accepted that during the first seven years from the time of the filling of the dam, 25% of the total methane emitted by the dam will be released. This is due to the methane released from the decomposition of the trees and grassland that is submerged. Thereafter emissions are from the decomposition of organic compounds entering and growing in the dam. (Rosa, 2000). In the oxic layer of water, carbon dioxide is produced by aerobic decomposition of dissolved and particulate organic carbon and methane as it diffuses up from the lower strata. In the anoxic layer organic matter is decomposed by methanogenesis, methane and carbon dioxide result (Rosa, 2002). In the case of the Inanda Dam there are two definite layers with regard to oxygenation, therefore it is expected that the above decomposition processes occur. Dissolved oxygen measurements are taken at 2 m depths, from the surface to the floor of the impoundment at weekly frequency (personal communication Steve Terry, Umgeni Water Environmental Division). The Inanda impoundment is anaerobic below 10 to 12 m from the surface in the summer months. In winter, for three months, turnover occurs and the impoundment becomes completely mixed and dissolved oxygen is transported to the lower layers and the impoundment is uniformly aerated. For this study a worst case scenario, which excludes winter turnover, was assumed.

All the literature surveyed (Rosa 2000, Rosa 2002, International River Network Report 2002, Louise et al., 2000, World Commission on Dams Report 2000) referring to the life cycle of dams deals with large dams and the greenhouse gases (carbon dioxide, methane and occasionally nitrous oxide) they release in relation to hydroelectric generation schemes. There is no study for dams used in the abstraction of water for human consumption. However, these studies on large dams show some important conclusions:

- Emission levels of greenhouse gases vary widely depending on the area and type of ecosystem flooded, reservoir depth and shape and the way the dam is operated.

- The ecological, physical and socio-economic characteristics of the catchment area feeding the dam will also influence emission levels by influencing incoming carbon.
- The decomposition of organics containing carbon is dependent on the ambient temperature and the temperature profile of the dam.
- There is a difference between the gases produced by aerobic as opposed to anaerobic decomposition. Anaerobic decomposition produces methane that has a higher global warming potential.
- Small quantities of nitrous oxide have been measured diffusing into the atmosphere from a few dams. The mechanisms of emission are not elucidated.
- The 100-year Global Warming Potential for methane as expressed in carbon dioxide equivalents may be higher in the case of dams. The Global Warming Potential is calculated as the total warming impact after 100 years due to a one-time pulse into the atmosphere of a given quantity of methane. In the case of dams the release of methane is continuous over long periods of time. Taking account this continuous release, the global warming effect after 100 years is considered to be 39.4 times greater than that of a pulse emitter (Raphals in the International Rivers Network Report, 2002). These results have to be validated and were therefore not used in the current research.

For the decommissioning stage, Bock (2004) calculates different emission scenarios for hydroelectric dams. She takes into account three decommissioning possibilities (no action, partial dam removal and full dam removal) and looks at the sedimentary deposits and their carbon content and how they may affect the environment. She discovered that by adding the greenhouse gas emissions due to decommissioning to the total release expected during the life time of the dam, the final global warming potential per unit of energy produced (kWh) was doubled. The conclusion from these theoretical calculations is that decommissioning of dams is important from a global warming perspective. In the absence of a valid decommissioning scenario for Inanda Dam, this problem has been overcome by assuming that all the carbon that enters the dam will be decomposed and transferred to the atmosphere and none will be sedimented.

1.3. Methodology

This section presents the methodology of calculating greenhouse emissions from the Inanda Dam.

1.3.1. Greenhouse Gas Emissions Model

Carbon dioxide and methane are two important gases produced in dams due to bacteria breaking down the organic matter in the water. Methane is produced in oxygen poor zones common at the bottom of the dam. The crucial input to consider to the dam is the total organic carbon (TOC) entering the dam. The TOC of water entering Inanda Dam is approximately 4.50 mg/l. This TOC decomposes and methane and carbon dioxide gases are produced. These are the harmful emissions from the dam that cause global warming. This is the only inventory aspect that was considered. A description of how these emissions were calculated is now presented.

The science of measuring emissions from dams is in its infancy. Currently there are no studies of the emissions from dams in South Africa. Therefore, in order to estimate missing data it was necessary to use measurements from Brazilian dams as these best approximate South African conditions (Rosa, 2000). The reason for choosing the Brazilian emission models was due to the fact that the volume of dam emissions is dependent on the ambient water temperature. Dams in the Northern Hemisphere in Canada have much lower emissions than dams in higher temperature regions. The Brazilian model is the closest to the temperature range of Inanda dam. Even though the temperature of the Brazilian dams are slightly higher than that of Inanda dam the science of calculating dam emissions is so inexact that it is better to over-estimate the emissions in order to present a worst case-scenario. Another reason why the Brazilian model was chosen was that the temperature profiles of the Brazilian dams studied closely match the temperature profile of Inanda dam. The ambient temperature and also the temperature profiles of the dam directly influence decomposition. These factors also influence the rate of decomposition not only for the initial carbon from the existing vegetation but also the carbon which is brought in by the river(s) feeding the dam. In a colder climate such as Canada, it is estimated that it takes 50 years for 60% of the submerged biomass to decompose. During this period only 5-10% of the carbon would undergo anaerobic decomposition and release methane. (Rudd et al., 1993).

Rosa (2000) in the Brazilian study takes the emissions into account in four ways; gross emissions from the reservoir, the net emission taking into account emissions prior to dam construction, carbon sequestration from the atmosphere by reservoir water and nitrous oxide emissions from the submerged soils. Measurements were carried out at the Balbina, Samuel and Tucurui dams in Brazil. A modified funnel was used to collect the gaseous emissions from the surface of the dam. It was found that in the younger reservoirs methane is emitted as bubbles and carbon dioxide by molecular diffusion.

For the three Brazilian dams in the first seven years after the filling of a reservoir, the main emissions are due to the decomposition of the biomass already existing in the flooded area before the dam was built. Measurements by researchers at COPPE/UFRJ at the Alberto Luiz Coimbra Institute in Brazil agree with this and show that the level of emission decreased with increased reservoir age, reaching a steady state period where it was hypothesised that the emissions are due to the biomass entering the reservoir. Using these measurements they were able to derive a model for predicting the emissions from a reservoir. This differs from the findings of Canadian researchers at UQAM who found that in Canada the rate of carbon dioxide emissions was independent of the age of the reservoir. It was hypothesised that this is due to the low temperature of the water, which does not allow the flooded biomass to decompose, and the emissions are mainly the result of biomass decomposition from the watershed (Rosa, 2000).

According to the measurements of the emissions by the Brazilians, the range of emissions is 1.49E-02 to 8-60E-02 kg CO2 equivalents per kilolitre water supplied by the dam. The emissions for the dams that are monitored in Brazil are presented in Table A1-1.

Table A1-1: Greenhouse gas emissions from a few Brazilian hydroelectric dams (Source: WCD, 2000)

Dam	Emissions (CO_2 equivalents)
Curua-Una	2.97E-02
Samuel	8.60E-02
Balbina	6.14E-02
Tucurui	1.49E-02

In order to determine the significance of the emissions from the dam, order of magnitude calculations were carried out. It is accepted that during the first seven years from the time of the filling of the dam, 25% of the total methane emitted by the dam will be released. This is due to the methane released from the decomposition of the trees and grassland that is submerged. Thereafter emissions are from the decomposition of organics entering and growing in the dam (Rosa, 2000). In the oxic layer of water, carbon dioxide is produced by aerobic decomposition of dissolved and particulate organic carbon and methane as it diffuses up from the lower strata. In the anoxic layer where organic matter is decomposed by methanogenesis, methane and carbon dioxide result (Rosa, 2002).

1.4. Results

This section presents the results of applying the greenhouse gases emission models.

1.4.1. Greenhouse Gases

Large dams have numerous impacts on the environment and using only the LCA tool many of these impacts could not be quantified. Therefore, it was possible to employ only a simplified LCA to take into consideration the emissions contributing towards global warming – which is the most important impact category for dams as established in the literature review section. To provide a better picture of the impacts of dams the LCA assessment was supplemented by using elements of an environmental impact assessment (EIA).

From a life cycle perspective, all of the material inputs into a dam and the greatest environmental disruptions occur during the construction phase. Once the dam wall and the infrastructure have been erected, the dam is filled with water and there are no material inputs (excluding the organic carbon) besides the maintenance of infrastructure. However, during the operation of the dam there are major outputs in the form of gaseous emissions. These result from the anaerobic decomposition of the vegetation submerged and the organic material brought by rivers into the dam. The lifetime of the Inanda Dam should be at least 70 years but is probably longer. There are no decommissioning plans/scenarios for the dam.

1.4.1.1. The Construction Stage

From the bill of materials from the construction of the dam the following data was extracted:

- Soft excavation 250 000 m^3
- Hard excavation 20 000 m^3
- Fill 1 400 000 m^3
- Concrete used 200 000 m^3.

Using this data, the amount of water extracted, and the lifetime of the dam, it was calculated that from the excavation and fill of the dam 3.77E-04 kg CO_2 equivalents have been released per kilolitre water extracted. From the concrete used 8.41E-03 kg CO_2 equivalents have been released per kiloliter water extracted. In total for the construction stage 8.8E-03 kg CO_2 equivalents per kilolitre of water are produced.

1.4.1.2. Operation Stage

The total organic carbon (TOC) entering the dam is 4.50 mg/l and the TOC leaving the dam is 3.35 mg/L (Terry, 2000). Using the Brazilian estimate that 30% (Rosa, 2002) of the entering TOC is converted to methane and the rest to carbon dioxide it was calculated that a worst case estimate of the emissions of greenhouse gases from Inanda Dam were 0.0511 kg/kL CO_2 equivalents. This method of calculating dam emissions is similar to that used by Liikanen (2002) and is a useful tool to get an estimate to use for order of magnitude calculations.

This means that for the construction and operation of the dam a total of 0.059 kg/kL CO_2 equivalents are calculated. It is assumed that during the decommissioning stage the dam will be drained and there will be no global warming emissions since no carbon is contained in the sediment. Therefore, the majority of the emissions will occur during the operation stage (85.3 %) and some (14.7 %) occurred during the construction stage. If the decommissioning plans change and the dam continues to contain water; methane and carbon dioxide will continue to be emitted.

These results are in line with the international ones obtained for hydroelectrical dams in the sense that the operation stage has the highest environmental burdens. However, there are differences in the order of magnitude. Cavalho and Bizo (1999) report that the greenhouse emissions due to construction are 40 times smaller compared to those due to operation. This is not the case with the current research results. This is due to the fact that the water is agitated during the electricity generation process resulting in a higher release of diffused gases. The size of the dam and the assumed lifetime may also play a role in these differences.

1.4.2. Discussion

Dams have resulted in loss of land, forests and resources. Fresh water fish have become endangered species, and even extinct. The impact downstream has been devastating, and it has been estimated that 60 million people worldwide have been flooded off their land and out of their homes by the construction of dams (Kasrils, 2000). However, with this is mind, it is not so easy or simple to make a blanket generalisation that dams are bad. Social decision making is problematic because competing individual preferences cannot, in general, be reconciled to produce universally agreed upon social preferences. In addressing the problem of ranking different objectives (Hertwich, 2000) in the case of dam construction, usually the decision to proceed is based on the ideology that the needs of the many outweigh the needs of the few, however, that does not mean that the few have to suffer.

The culture of forced removals has been replaced in South Africa by one of co-operative involvement. In a recent scheme called the Berg River Project in the Western Cape region, the affected communities were involved in the decision making from an early stage (Liane Greeff personal communication). In fact the final relocation terms proved to be so attractive that even people who were not affected were clamouring to be included. This is an example of how a dam can have a positive social impact.

South Africa is in the process of considering a new protocol for water resource development as part of the National Water Resources Strategy guiding the implementation of the National Water Act promulgated in 1998. The protocol represents a departure: from the supply side dominated engineering paradigm currently guiding many of the water decisions in our country and in many places in the world toward one that embraces the core principles of integrated resource planning (Naidoo, 2000). The adoption of this protocol will have many positive political, economic and social implications for communities in developing countries, as affected communities will be involved in all stages of the development process.

1.5. Conclusion

For the abstraction of water a simplified LCA (only global warming) was performed as most of the LCA impact categories are unsuited for this type of assessment. The most important environmental and social impacts due to the abstraction of water could not be included in the LCA assessment and therefore these impacts have been investigated separately. Most of the greenhouse gases due to the dam are from the operation stage and a relatively smaller contribution from the construction stage.

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"Once upon a time, dams were the so-called marvels of engineering, and these were presented as a kind of conquest on nature. They were typically described or photographed from a great height looking down as though it was God's eye viewing these marvels. And the implications were very clear; that the man-made constructs were almost more powerful than nature, and certainly more significant than mere human beings." (Ronnie Kasril, SA Minister of Water Affairs and Forestry, 1999).

Appendix 2 : Sludge disposal to sea

The most important environmental issue with regard to the disposal to sea of effluents is ecotoxicity and human toxicity to the marine and shore environment. This chapter presents the current practice with regard to the disposal of effluents and the toxicity issues surrounding this practice. Direct toxicity test were performed by bioassay tests on sea urchins. The results of these tests were then converted into LCA toxicity scores by using an internal standard. This appendix is based on work done by Friedrich and Pillay (2005).

2.1. Current Practice

The municipality of eThekwini has disposed effluents to sea since the end of the 19th century. However, since the 1960s stable, researched, planned and engineered submarine outfalls have been operated. The Southern Wastewater Works Outfall started to discharge in November 1968 (McClurg and Connell, 2003) and has been operational ever since. This outfall is situated near the mouth of the Mlaas canal and carries effluents from the Southern Wastewater Works that serves the southern city catchment. Since the recycling plant started operating it also carries the sludges resulting from the recycling process. The recycling plant is supplied with water from the secondary treatment section. In the recycling plant water is extracted from the effluent and the sludges are sent to the sea outfall. Prior to the installation of the recycling plant, sewage from the secondary treatment plant was sent directly to the deep-sea outfall for discharge.

The Southern Wastewater Works Outfall is a submerged pipeline with a length of 4.2 km and the main diameter of 1.37 m. The length of the diffuser section is 290 m and it has 34 diffusers. These diffusers are located at an average depth of 54 to 64 meters. The design capacity of the pipeline is 230 ML/d.

The outfall pipelines managed by the eThekwini Municipality are operating on a renewable permit system issued by the Department of Water Affairs and Forestry. The discharge of complex wastewater, as from the Southern Wastewater Works, is prohibited under the National Water Act (Act 36 of 1998) and is only allowed under a renewable permit system if certain conditions are satisfied. In the case of the Durban outfalls, these conditions involve careful monitoring of the discharge, surveys assessing the impacts on the receiving environment and physical inspection of the outfalls in order to check integrity and efficient functioning (McClurg and Connell, 2003). The environmental monitoring programme started in the 1960s before the first discharge (baseline data) and at the moment it has four major areas: microbiology, benethic ecology, environmental chemistry and effluent toxicity (McClurg and Connell, 2003). They will be briefly described in the following sections.

Microbial sampling for the Durban Outfalls commenced in 1964 at a number of sampling stations on the beaches and shorelines of the city. With time the number of tests have increased and at the moment, besides coliform contamination, the presence of staphylococci, salmonellae, shigellae, parasite ova and depressed salinity are investigated. Based on this battery of tests a score system was developed in order to assess the overall microbiological quality of seawater and to classify Durban beaches. In addition the presence of coliphages and viruses are tested for regularly (McClurg and Connell, 2003) providing additional information on microbiological contamination. More details on the microbiological monitoring is presented in McClurg and Connell, 2003.

Similar to the microbiological monitoring, the benethic ecology monitoring started in 1964, before the first discharge to sea. The benethic component of the marine ecosystem was chosen because it contains the most vulnerable species that are immobile and can not escape unfavorable conditions. In 1994 the monitoring was extended to include more sampling stations and larger samples. This enables more detailed analysis and the investigation of the relationships between the animals sampled and the chemical and physical characteristics of the seabed.

Environmental chemistry was used in the monitoring of chemical elements and compounds in receiving waters, sediments and accumulator organisms such as mussels and oysters. These complemented the regular chemistry analysis from effluents done by the municipality laboratories (McClurg and Connell, 2003). In the receiving waters in the vicinity of the outfalls, key trace metals in the seawater are investigated. The problem with this type of monitoring is mainly with sampling in the dynamic water column, however, this method was able to pick up mercury discharges in the late 1980s and led to the solution and control of such incidents. Trace metals are also investigated in the sediments and in mussels and oysters. In addition to trace metals, recently, sampling and analysis for chlorinated pesticides have been done (McClurg and Connell, 2003).

The combined toxicity of the effluent is tested using sea urchin eggs. The methodology employed is described in Section 2-3 These tests measure the percentage fertilisation and the dilutions needed to render a sample as non-toxic, i.e. the minimum dilution at which fertilisation is not significantly different from pure seawater. The number of dilutions is then compared with the design parameters of the system. The effluent currently requires 200 dilutions in seawater and the system is designed to achieve 330 dilutions within the mixing zone.

The outfalls monitoring programme, as presented in the above sections, has been critically reviewed in 2003 by an independent applied marine scientist. The Wildlife and Environment Society of South Africa initiated this revision. It was conducted on three different levels: compliance monitoring, precautionary monitoring and effects monitoring. Each of these monitoring components was evaluated against their underlying requirements of producing information useful for the management of the marine outfalls and currently accepted monitoring theory and practice (Carter, 2003). In general the review concludes that the compliance monitoring is adequate and the toxicity testing adds additional strength. For the precautionary monitoring there are some suggestions of improvement with regard to sampling (i.e. water columns sampling, sediment sampling grid, beach sampling points, sampling intervals etc.). For the effects monitoring programme, the reviewer also presented suggestions for improvement. Most notably the incorporation of reference sites, strengthening of the statistical basis and the incorporation of cumulative effects into the monitoring programme (Carter, 2003).

In summary, the Southern Wastewater Works Outfall has been operating since the late 1960s discharging a mixture of domestic and industrial effluents to the sea. Recently a water recycling plant has been commissioned and the composition of the effluents has changed slightly. To monitor the environmental impacts due to the outfall a series of monitoring studies have been conducted. So far these tests have picked up and helped trace and manage impacting events such as mercury discharges (1987 and 1993), unlawful waste discharges (1997) and natural events (the 1987 floods). The monitoring programme has been recently reviewed and suggestions for improvement have been put forward.

2.2. Ecotoxicity Issues

The effluent discharged from the Southern Wastewater Works Outfall is a complex mixture of domestic and industrial effluents; chemical analyses of these effluents can never satisfactorily cover all the possible constituents. Complex effluents may have different environmental effects than the sum of individual substances due to inter-reactions between components but also due to cumulative effects. The effluent composition may vary in time, with different batches and having a multitude of tests done for each batch requires time and financial resources. The battery of tests employed in the monitoring programme provides a good picture, however, only the bioassay toxicity test, which uses sea urchin eggs, measures the actual effects of the complex discharge and takes into account cumulative effects. The problems associated with complex effluents and their toxicity are acknowledged in scientific and regulatory circles and different direct bioassays toxicity test are in use. In South Africa the Department of Water Affairs and Forestry produced, in 2003, a discussion document entitled The Management of Industrial Wastewater Discharges – Introducing the Direct Estimation of Ecological Effect Potential (DEEEP) Approach. It envisages the introduction of tests for measuring acute toxicity, chronic toxicity, bioaccumulation, mutagenicity, persistence and endocrine effects due to wastewater.

Bioassays and ecotoxicity LCA scores represent two different methods in measuring and expressing ecotoxicity. They are based on two different approaches. The bioassays are direct toxicity assessments and they provide direct measurements of the quality of a given sample, in this case of the quality of the effluent discharged through the Southern Wastewater Works Outfall. Ecotoxicity LCA scores are calculated and inferred toxicity measurements based on the toxicity of each substance of the system investigated. Therefore, it is a substance specific assessment and the scores sum up the toxicity associated with a functional unit in an LCA study. For a better overview of the two different approaches, a comparison of a substance specific assessment and a direct toxicity assessment is presented in Table A2-1.

Since it is impossible to determine all the chemical components in the effluent from the Southern Works Outfall, it was impossible to calculate direct LCA scores for aquatic toxicity for the disposal to sea of this effluent. To overcome this problem the toxicity data from the sea urchin bioassay test was converted to LCA scores by the means of an internal standard in the form of formaldehyde. This substance was used as an internal standard since it is already the reference toxicant for the sea urchin test and in the LCA scoring system it had a defined equivalency factor.

Table A2-1: Advantages and disadvantages of substance specific assessments and direct toxicity assessments with regard to ecotoxicity of complex effluents (Source: Scottish Environmental Protection Agency, 2003)

Substance – Specific Assessment	Direct Toxicity Assessment
Disadvantages	*Advantages*
Does not measure biological effect of substance present	Detects combined biological effect of all substances present
Cannot control substances where no effect levels or biological test data exist	Controls toxicants for which no effect levels exist
Does not account for interaction between substances present	Accounts for chemical and toxicological interactions
Analytical costs increases greatly with complexity of the effluent	Monitors complex effluents without increasing cost of testing for increasing number of components
Can only monitor substances where appropriate analytical methods and limits of detection exist.	Monitors toxicity where methods of chemical analysis are unavailable
Advantages	*Disadvantages*
Can monitor bioaccumulable substances that cause chronic toxicity by long term uptake	Does not detect bioaccumulation
Can identify single substances responsible for toxicity	Cannot identify causative single substances
Relatively quick and inexpensive method of controlling simple effluents of a well defined and consistent composition	Relatively slow and expensive compared to chemical analysis of a small number of easily analysed determinants
Should ensure compliance with no observed levels for a given substance where these exist for a given water use	Detects only that toxicity which is ‘measured” by the test species (hence the need to use a battery of tests on a variety of species)

2.3. The sea urchin bioassay and the calculated aquatic toxicity LCA scores

To determine the overall acute toxicity of the effluent in the marine outfalls sea urchin bioassays have been used in Durban since the late 1980s and reliable sequential data is available since 1988. The methodology involved in these tests is described in detail in the relevant technical report (National Institute for Water Research 1986) and a summary is presented as follows.

Urchin sperm is added to dilute effluent in seawater and allowed to swim for exactly 10 minutes. Nearly spawned eggs are then added to each vial and fertilisation is allowed to proceed for the 10 min. following. After precisely 20 min, formaldehyde is added to each vial, to terminate the test.

A fertilised sea urchin egg forms an easily discernible hyaline membrane immediately upon being fertilised. Thus relative fertilisation can be assessed for each vial. Control vials, containing pure seawater, are used as checks and to supply data to compare the vials containing effluent. By using serial dilutions (e.g. 1:100, 1:200, 1:500, 1:1 000) a series of points is obtained from each test, which can be presented in graph form. Each dilution is replicated four times to improve the statistical value of the tests.

From the variation in relative fertilisation within replicates and between dilutions, the variability of the test is calculated as are confidence limits within which all test results should fall if the effluent had no effect on the result. Results falling outside these limits would indicate a significantly reduced fertilisation caused by the presence of toxicant in the water. The mean fertilisation of the controls in the test, adjusted down by 1 standard deviation, yield a straight line across the top of the graph. The mean fertilisation from each test dilution, plotted on the same graph, will typically yield a sigmoid curve. The point, at which this curve intersects the x-axis, will provide the Minimum Acceptable Toxicant Dilution (MATD). This is the minimum dilution in seawater at which the test fertilisation was not significantly different from the controls of pure seawater. The gametes of the urchin *Echinometra mathaei* were used in the tests. For this study grab samples of effluents were collected from 8 points within the treatment and recycling plant as shown in Figure A2-1.

The sample points were:

1. Entrance to the activated sludge
2. Waste activated sludge
3. Exit from the activated sludge
4. Exit from the lamellae settlers
5. Exit from the dual media filters
6. Exit from the granular activated carbon filters

7. The tertiary sludges from the recycling plant going to the sea outfall.

8. The final effluent to sea.

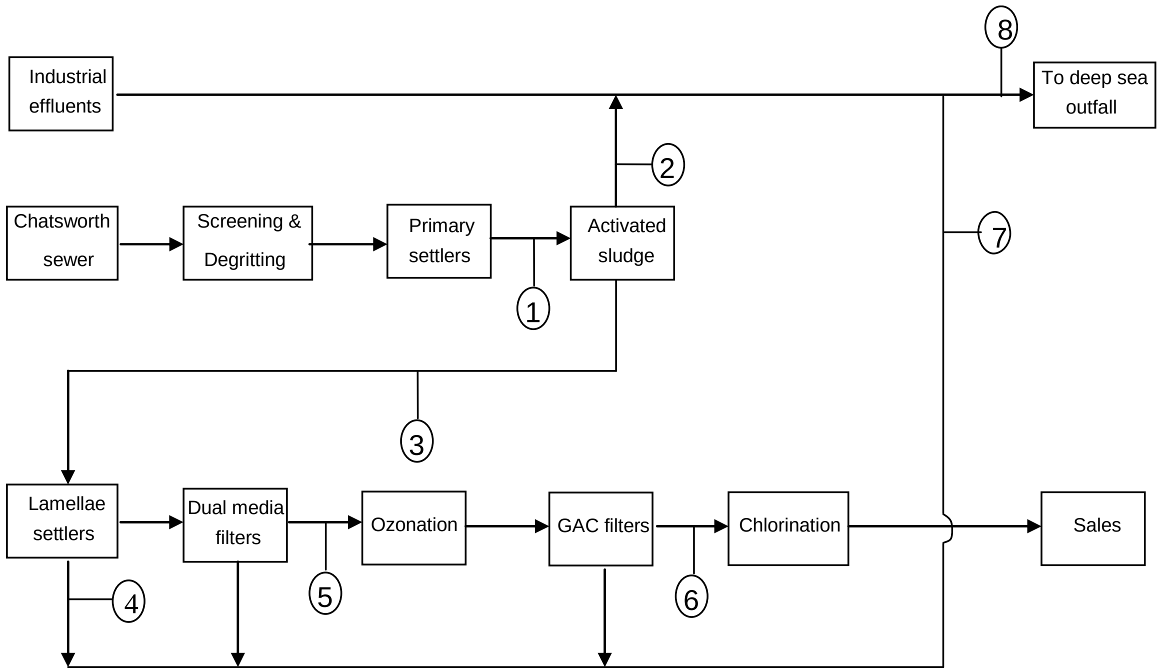

Figure A2-1: 1 Flow diagram of the Southern Wastewater Treatment Works showing the sampling points for the acute toxicity tests.

A summary of the results is presented in Table A2-2.

Table A2-2: MATD values of samples taken from the Southern Wastewater Treatment and the Recycling Plant

No.	Sample	MATD
1	Entrance to the activated sludge process	12
2	Waste activated sludge	8
3	Exit from the activated sludge	8
4	Sludge exit from the lamellae settlers	7
5	Exit from the dual media filters	8
6	Exit from the granular activated carbon filters	8
7	Tertiary sludges	264
8	Sea outfall	43

The MATD mean values for the pipeline for the last four years (1998-2002) are in the range of 100 to 200. The highest ever-recorded MATD at the Southern Works was in 1991 and was about 375 MATDs. Most of the MATD toxicity values measured inside the wastewater and the recycling plant are well below this range, the only exception being the tertiary sludges. This increased toxicity is explained due to the high concentration of these sludges. They are then diluted with the industrial effluent and the overall toxicity of the outfall effluent was measured at 43 MATDs. The MATDs for samples 2,3,4,5 and 6 are almost the same, which means that the toxicity within the treatment and the recycling plant does not change much. The addition of the chemicals used for the production of industrial grade water from wastewater does not change acute toxicity at the detection limits of this test. The acute toxicity of the final effluent which is pumped to sea (sample no 8) is well within the design parameters of the pipeline (330 dilutions within the mixing zone).

For the toxicity tests formaldehyde of analytical grade in a concentration of 37% volume was used. At 20 °C the density of formaldehyde is 0,815 g/mL. This means 301,55 g/L formaldehyde. By using this information and the data from the individual toxicity tests the concentration of the sample was calculated in order to obtain the same toxicity levels as the samples themselves. The results are presented in Table A2-3. In addition, in the third column, the calculated equivalent aquatic toxicity score is presented for each of the eight samples. The aquatic toxicity LCA scores are expressed in kg DCB (dichlorobenzene) equivalents. For the conversion of the concentration of formaldehyde into DCB equivalents the equivalency factor of formaldehyde in the LCA methodology was used. This factor is 0.00625 (1/160); in other words 1 kg of formaldehyde is 160 times more potent in terms of aquatic toxicological effects than 1 kg of dichlorobenzene. Columns four and five present the average flow rates and the calculated masses of toxicity.

Table A2-3: The bioassay acute toxicity results and the calculated LCA scores

Sample No and Stream	Concentration (g/l)*dilution for formaldehyde	LCA aquatic toxicity scores* (kg DCB eqv)	Avg flow rates (L/day)	Actual mass of aquatic toxicity (kg DCB eqv/day)*
1 - wastewater from domestic user after settling	0.0177	1.1E-04	34 155	3.787
2 - sludge from the activated sludge process	0.0151	9.4E-05	602	0.057
3 - effluent after activated sludge process	0.0144	9.0E-05	33 553	3.011
4 - sludge from the lamellae settlers	0.0144	9.0E-05	Not measured	N/A
5 - recycled water after dual media filters	0.0144	9.0E-05	Not measured	N/A
6 - recycled water after GAC filters	0.0144	9.0E-05	32 385	2.906
7 - combined sludges from the recycling operation	0.3769	2.4E-03	1451	3.418
8 - industrial effluent (not treated) mixed with sludges from the recycling operation – to sea	0.0685	4.2E-04	176 828	75.742

* The aquatic toxicity scores are expressed in kg DCB (dichlorobenzene) equivalents.

If one considers the individual processes within the wastewater treatment plant (as in the flow diagram in Figure A2-1) the MATDs and the resultant LCA scores reveal that in terms of aquatic toxicity there is only a slight reduction (from sample 1 to sample 6). In addition a series of chemicals are used, which contribute to the improvement of other parameters defining the quality of the water. Therefore, the aquatic toxicity from the sludges is the local environmental trade-off for the improvement of the quality of the wastewater.

Because of the methodological problems with measuring and expressing toxicity these scores have to be seen as an academic exercise and therefore extrapolations outside this study are not advised. Another shortcoming of this research is that in the direct assessment of toxicity only one species – the sea urchin *Echinometra mathaei* - was used. Environmental bioassay applications are scarce in South Africa and in effluent monitoring they are only applied in Durban. More advanced bioassay protocols for the monitoring and regulating of complex effluents have been produced and are used in the USA, Canada and the UK. These protocols usually involve bioassays performed on more than one species and in general species from different trophic levels (i.e. phytoplankton, intermediate predator and top predator species) from within the receiving ecosystem. Further research should develop similar protocols for South Africa and in particular for its marine shorelines.

2.4. Comparison with Other Toxicity Scores

This section compares the different acute toxicity scores. From Table A2-4 it can be seen that the deduced scores for tertiary sludges, which are the direct aquatic toxicity going out to sea due to the recycling of water, is of the same order of magnitude as the calculated aquatic ecotoxicity LCA scores from the primary, secondary and tertiary treatment.

Table A2-4: AquaticToxicity Scores per kL Wastewater

Impact (kg DCB eq)	Primary Treatment	Secondary Treatment	Tertiary (due to processes)	Tertiary sludges to sea	Outfall
Aquatic ecotoxicity	1.80E-03	4.77E-03	1.00E-03	2.40E-03	4.27E-04

Since the processes involved in the generation of aquatic ecotoxicity due to the treatment of wastewater are geographically scattered (e.g. aquatic toxicity due to the production of chlorine occurs at another location than the water treatment plant) it can be concluded that global and regional toxicity impacts are similar to the local ones for the treatment and recycling of water. This opens the questions of environmental efficiency and how one evaluates environmental trade-off between different geographical locations and also between different environmental impact categories (e.g. clean water vs. pollution due to generation of electricity). To answer these questions more research is needed, not only in the area of LCA and water management but also in the area of environmental valuation.

2.5. Summary

The direct toxicity of complex effluents cannot be assessed satisfactorily by using LCA methods and complimentary bioassay tests have been used. The scores calculated lead to the conclusion that local environmental trade-offs for the treatment and recycling of water are smaller than regional and global ones. This opens the questions of environmental efficiency and environmental trade-off between different locations. When comparing the bioassay acute toxicity scores with the calculated LCA scores for the treatment of wastewater it can be concluded that the acute toxicity in the wastewater disposed to sea is less than the toxicity due to the treatment processes.

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Appendix 3 : Urine Diversion Toilet

For future developments the eThekwini Municipality (ETM) subscribes to the principles of ecological sanitation (Eco-San). The key principles of Eco-San are the provision of effective and sustainable sanitation to all peoples of the world and 'closing the loop' between sanitation and agriculture. For Esrey et al (1998) the goals of Eco-San are: to render human excreta safe, to prevent pollution rather than attempt to control it after the fact, and to use sanitised human excreta for agricultural purposes. Winblad (1997) coined the 'don't mix!' slogan which is the part of the general Eco-San aim of keeping faeces, urine and greywater separate. The urine diversion (UD) toilet is the sanitation method of choice.

An estimated 95% of wastewater generated worldwide is released without treatment (Niemczynowicz, 2000). This is particularly applicable to Durban where most of the wastewater is pumped out to sea. Thus by using UD toilets there is a double benefit of reducing the amount of wastewater to the sea and the benefit from the waste being used as a fertiliser.

eThekwini's choice of on-site sanitation technology was based on the operational and maintenance requirements of the system. It concluded that conventional ventilated improved pit latrines were not sustainable in an urban context as over time the pits filled and there was often not enough space on-site to build replacement pits. The only alternative was to desludge these pits. Regular emptying was not affordable to the municipality. Moreover, many areas are inaccessible to the city's tankers (Innovation Insights, 2004)

This appendix examines the working of the urine diversion toilet and presents some of the main environmental impacts.

Urine separation has been used in combination with compost toilets for centuries in Yemen and Vietnam (Winblad, 1997). The type of urine diversion toilet adopted by the eThekwini Municipality consists of two chambers or vaults above or slightly below the ground. Waste is deposited in the chamber and dry organic material such as wood ash, straw or vegetable matter is added after each use to deodorise decomposing faeces and/or control moisture and facilitate biological breakdown. Urine is separated/diverted through use of the specially adapted pedestals. The urine may be collected and used as a fertiliser. The following description of the workings of the toilet is taken from business plan of the eThekwini Municipality.

The vaults consist of block work chambers with an impervious floor- the size of the vault is 0.926m^3. The superstructure consists of brick walls having internal dimensions of 1160mm by 910mm wide. The roof is galvanised sheets 0.6mm thick. The floor of the toilet consists of 40mm thick reinforced precast panels that are transported to site and then, once placed in position, receive an in situ structural topping.

Pipe work is cast into the structural topping and is designed to allow urine to be diverted to an external soakaway positioned some metres away from the toilet.

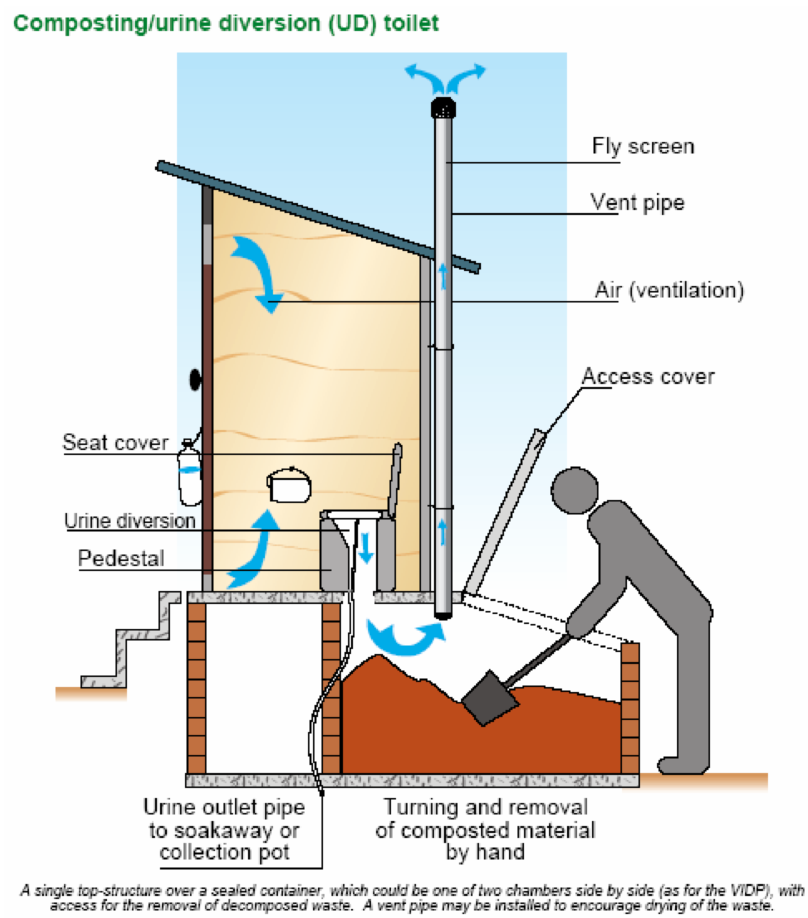
Holes in the floor slab allow a pedestal to be positioned over one of the vaults while the other is covered with a plug. The pedestal is designed to allow urine to be collected separately and flow via the soakaway, into the surrounding soils (as opposed to being allowed to mix with the faecal matter). The pedestal is designed so that it can be moved from one vault the other. As the UD toilets are used mainly in rural areas which generally have a small food garden the urine can also be collected and used as a fertiliser.

While the faecal matter is being collected in the one vault, the other is kept empty. Additional sand (ash, lime or soil) is added to the faecal matter to assist drying. The contents of a chamber needs to be regularly agitated e.g. the pile needs to be flattened.

When the first vault is full, the pedestal is moved and positioned over the second vault. The first vault is then sealed off, and the contents allowed to dehydrate and solidify until the second vault is full. When the second vault is full, the contents of the first vault is then emptied and disposed of. The first vault is then used to collect the faeces while the contents of the second is allowed to dehydrate and solidify. The cycle is then repeated as many times as required. The dried faecal matter is disposed of, by the householder, by digging a hole in the ground and burying it. In this way the nutrients are returned to the soil.

The urine diversion toilet does not accept domestic wastewater. The cost of operating the toilet is between R35 and R500 per annum, depending on local government involvement and householder willingness to handle waste, and disposal options. Figure A3-1 shows a sketch of a urine diversion toilet.

Figure A3-1: Diagram of a urine diversion toilet



In an LCA study on the environmental impacts of UD toilets Lundin found that (Lundin, 1999) urine separation had low emissions to water and efficient recycling of nutrients (especially nitrogen, but also phosphorus). However in this system the separated urine and faeces were transported to a treatment facility before being disposed of or recycled as in the case of the urine.

Bengston (1997) found that in using the discharges from the toilet as a fertiliser a twofold environmental benefit is achieved. Firstly, the nutrients that are made available to plants reduce the need for commercial fertilisers. Secondly, bringing the nutrients (such as phosphorus and nitrogen) to soil so that they can be fixed in plants means that emissions to air and water are reduced.

A number of factors affect the availability of nutrients to plants, and it is difficult to find any data that can be generalised since this is an area of high biophysical complexity. A study currently being undertaken by the Pollution Research Group of the University of Kwa-Zulu

Natal examines the effects of using the UD toilets products as a fertiliser on the kind of crops found in a typical rural garden. Preliminary results are promising with UD fertilised plants performing better than their normally unfertilised counterparts.

The emissions from the UD toilet discharge are small. Bengtsonn (1997) showed that the emissions are largely due to ammonia released from the urine during the spreading. Large variations in these emissions are likely to occur, since this is very much dependent on a number of factors that are hard to control such as climate and wind. For the purposes of evaluating the scenarios the emissions pertaining to global warming were considered. Bengtsonn showed that these emissions are relatively small and accrue mainly from the transport of the urine to nearby farms. Since the urine is used on-site in Durban it was assumed that the emissions of global warming gases were negligible and hence the score for this category is zero.

The ammonia emissions contribute the acidification impact category. The UD toilet can also be configured (and this is usually the case in Durban) to give a sub-soil release of the urine. This aids in greatly reducing the ammonia released into the atmosphere and increases the nitrogen available to the soil.

It is important that the faeces be buried and not spread directly on the fields as a fertiliser. The faeces contain approximately 10^{10} micro-organisms per gram dry matter (Lentner et al., 1981) and some of them can be pathogenic. Users of the toilets are encouraged to regularly spread ash over the faeces. This has the effect of raising the pH which disinfects the faeces. The effectiveness of this method depend on the amount of ash used and the origin of the ash, since the amount of available hydroxide ions varies. Studies on *Salmonella typhimurium* phage 28B and faeces treated with ash have shown a die-off from 8 $\log_{10}$ after three weeks of storage down to 2 $\log_{10}$ in seven weeks, in different toilets in Vietnam (Carlander and Westrell, 1999). In the same study, the reduction in viable *Ascaris* was also monitored. During the nine weeks of monitoring, the reduction compared to the blank reference was between 50% and 100% (no viable eggs were found). In the ETM case it must be remembered that the faeces from each vault will have a minimum drying time of 18 months and thus if used properly the risk of pathogen transmission is minimal.

One must remember that the UD toilets can only be used in areas where subsoil conditions are permeable enough to ensure that the effluent does not surface. Overall urine diversion toilets have been investigated in a number of other environmental systems analyses using both the methods of LCA and substance flow analyses (Bengtsson et al., 1997; Tidåker & Jönsson, 2001; Kärmann et al., 1999). Considering the environmental impacts and the resources used they all concluded that urine separation is preferable to conventional sewage. This seems to hold under most conditions and assumptions.

3.1. References

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Appendix 4 : Data quality indicators

To assess the quality of data, a score system for data quality indicators was used. This system was developed by Weidema (1997) and the different scores are explained in the following table.

TableA 4-1: Pedigree matrix with data quality indicators

	Reliability	Completeness	Correlation		
SCORE			Temporal	Geographical	Technological
1	Validated* data based on measurements**	Representative data from a sufficient sample of sites over an adequate period to level out normal fluctuations	Less than 3 years of difference to year of study	Data from area under study	Data from enterprises, processes and materials under study
2	Validated data partially based on assumptions or non-validated data based on measurements	Representative data from a smaller number of sites but for adequate periods	Less than 6 years of difference	Average data from larger area in which the area under study is included	Data from processes and materials under study but from different enterprises
3	Non-validated data partly based on assumptions	Representative data from an adequate number of sites but from shorter periods	Less than 10 years of difference	Data from area with similar production conditions	Data from processes and materials under study but from different technology
4	Qualified estimate (e.g. by industrial expert)	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Less than 15 years of difference	Data from area with slightly similar production conditions	Data on related processes and materials but same technology
5	Non-qualified estimate	Representativeness is unknown or incomplete data	Age of data unknown or more than 15	Data from unknown area or area with very	Data on related process or materials but

	Reliability	Completeness	Correlation		
SCORE			**Temporal**	**Geographical**	**Technological**
		from a smaller number of sites and/or from shorter periods	years of difference	different production conditions	different technology

The purpose of such a matrix is to provide an overview with regard to data quality. The methodology has been applied to the data collected for the system. As explained in Chapter 3-2-2, the processes were divided into *background* and *foreground* processes. The *background* system is that which supplies materials and energy to the *foreground* system, usually via a homogenous market so that individual plants and operations cannot be identified. For example, commercial databases were used for raw material extraction, material production and energy production. The *foreground* system is defined as the set of processes directly affected by the study. Processes of the primary suppliers and processes within the plant are defined as *foreground* and site specific data are collected.

Thus reliable data had to be collected for the foreground processes. The quality of the data collected is evaluated in the table below;

Table A4-2: Pedigree Matrix for the Data collected for the System

Process	**Reliability Score**	**Completeness Score**	**Correlation Scores**		
			Temporal	**Geographical**	**Technological**
Construction Stage					
Cement Production	1	1	1	1	1
Stone Production	2	2	2	2	2
Sand Production	2	2	2	2	2
Steel Production	2	2	3	3	3
Stainless Steel Production	2	2	2	3	3
Copper Production	2	2	2	3	3
Aluminium Production	2	2	2	3	3
PVC Production	2	2	2	3	3
Asbestos cement	2	2	3	4	4

Process	Reliability Score	Completeness Score	Correlation Scores		
			Temporal	**Geographical**	**Technological**
Vitrified clay	3	3	5	5	5
Operation Stage					
Bentonite Production	3	3	5	5	5
PAC Production	4	4	4	4	4
Oxygen Production	1	2	1	1	1
Coagulant Production	3	5	3	5	3
NaOCl Production	1	1	3	3	3
Slaked Lime Production	2	2	3	3	3
Chlorine Production	2	2	3	3	3
Filtration Sand Prod.	2	2	2	2	2
Electricity Generation	2	2	3	4	4
Ferrous sulphate Prod.	2	2	1	2	2
Decommissioning Stage					
Recycling of Steel	3	2	3	4	4
Recycling of Copper	3	2	3	4	4
Recycling of Aluminium	3	2	3	4	4
Landfilling of PVC	4	4	4	4	4
Average	2.3	2.3	2.7	3.2	3.1

The data for which the quality is low (i.e. having a high score) is mainly for chemicals and raw materials that are either imported or proprietary technology.

4.1. Reference

Weidema P. B., (1997) Environmental Assessment of Products, The Finnish Association of Graduate Engineers, Helsinki, Finland.

Appendix 5

INVENTORY DATA