THE USE OF LIFE CYCLE ASSESSMENT IN THE SELECTION OF WATER TREATMENT PROCESSES

Final Report to the
Water Research Commission

by

E Friedrich and CA Buckley

Pollution Research Group
School of Chemical Engineering
University of Natal
Durban 4041

WRC Report No 1077/1/02
ISBN No 1 86845 858 X
March 2002

EXECUTIVE SUMMARY

Introduction to the Project

In the context of sustainable development, life-cycle assessment (LCA) is emerging as one of the tools of cleaner production. 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 (environmental) burdens* (Kloepffer, 1997). Therefore, it provides a holistic view of the environmental impacts due to a product, service or activity. The LCA methodology enables the calculation of environmental burdens in a systematic and scientific way by regarding all the inputs and outputs of a system. Hence, it allows for comparison on environmental grounds. Due to these unique characteristics, this tool was used to assess the environmental burdens resulting from the production of potable water.

This study compares the environmental burdens resulting from two different technologies used in the production of potable water in South Africa. The first one is the *conventional technology* and is currently employed at Wiggins Waterworks, a waterworks of Umgeni Water situated in Durban, South Africa. The main processes involved are preozonation, addition of chemicals, flocculation, sedimentation, filtration, ozonation, chlorination and storage. The second technology is based on the use of an emerging South African *membrane filtration* method, and the following processes are involved: prefiltration, membrane filtration, chlorination (different to the previous technology) and storage. There are three pilot plants employing this membrane technology in South Africa.

The environmental impact categories, on which the performance of the two technologies of producing potable water are compared, include global, regional and local impacts (global warming, ozone depletion, smog formation, acidification, nutrient enrichment, ecotoxicity and human toxicity). All inputs and outputs for the production of potable water, by the two technologies, are listed and quantified separately. This is followed by a calculation of the contributions by the two technologies to each of the environmental impact categories considered. The inputs from processes involved in the production of water include energy inputs as well as raw material inputs. The outputs include products, by-products as well as emissions to air, water and soil.

The aims of the study are defined as follows:
- to improve the total environmental performance of selected water treatment processes,
- to guide designers and owners of water on the full life cycle environmental consequences of selected treatment processes,
- to alert the water industry to the benefits of using full life cycle assessment in the selection of processes, and
- to develop capacity in undertaking life cycle assessments.

Therefore the specific objectives of the study are:
- to conduct life cycle assessments for one conventional and one membrane water treatment technology, and
- to compare the environmental burdens associated with each process.

Background to Life Cycle Assessment

The life cycle assessment (LCA) is an environmental tool dealing with the complex interaction between the environment and a product or activity; taking into account all the impacts due to the use of raw materials and all the emissions produced.

Definition of environmental life cycle assessment

In the International Organisation for Standardisation (ISO) 14040 standard (1997), the definition of LCA is given as follows:

> *LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by*
>
> - *compiling an inventory of relevant inputs and outputs of a system,*
> - *evaluating the potential impacts associated with those inputs and outputs,*
> - *interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.*
>
> *LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health and ecological consequences.*

The definition given above presents the three main stages of an LCA study, and subsequent ISO standards (ISO 14041, 14042 and 14043) elaborate further on the method involved in these stages.

Stages and methodology

The ISO 14040 series of standards have been produced in order to develop a consistent approach in conducting LCAs. This study follows the methodological procedures laid out by the ISO documents. This procedure sets four phases, which have to be part of an LCA. These phases are: goal and scope definition, inventory analysis, impact assessment and interpretation.

Goal and scope definition is the first step in an LCA study. Defining the goal of the study should address issues like intended applications, reasons for doing the study and the intended audience. In addition, the initiator should be mentioned (Heijungs et al., 1992). Under the scope of the study, the ISO documents recommend the following issues be considered and defined: the function of the product system, or, in the case of comparative studies, the systems; the functional unit; the product systems boundaries; allocation procedures; data requirements; assumptions; limitations; type of critical review, if any; and type and format of the report required for the study. From this array of issues, special attention has to be given to 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 potable water at the quality stipulated in the Umgeni Water guidelines produced over the life period of a process unit at a capacity of about 200 ML/day. In comparative studies like this one, the functional unit sets the scale for comparison (Jensen et al., 1997) and **Fig. 1** presents the framework for this comparison and the main processes involved for each technology.

The *inventory phase* forms the core of an LCA and is the most time consuming part. It involves data collection and calculation procedures to quantify relevant inputs and outputs of a process. Process inputs can be divided into two categories: environmental inputs (raw materials and energy resources) and economic inputs (products, semi-finished products or energy - they are outputs from other processes). Similarly there are two kinds of outputs: environmental outputs (emissions to air, water, soil) and economic outputs (products, semi-finished products or energy). For example, in the conventional technology of producing potable water, 35 processes were investigated. These included processes such as cement production for the construction of the waterworks and the production of electricity and chemicals (chlorine, ozone, powdered activated carbon, polymeric coagulant, sodium hypochlorite etc.) used in the operation stage. It also includes disposal processes for the decommissioning of the waterworks.

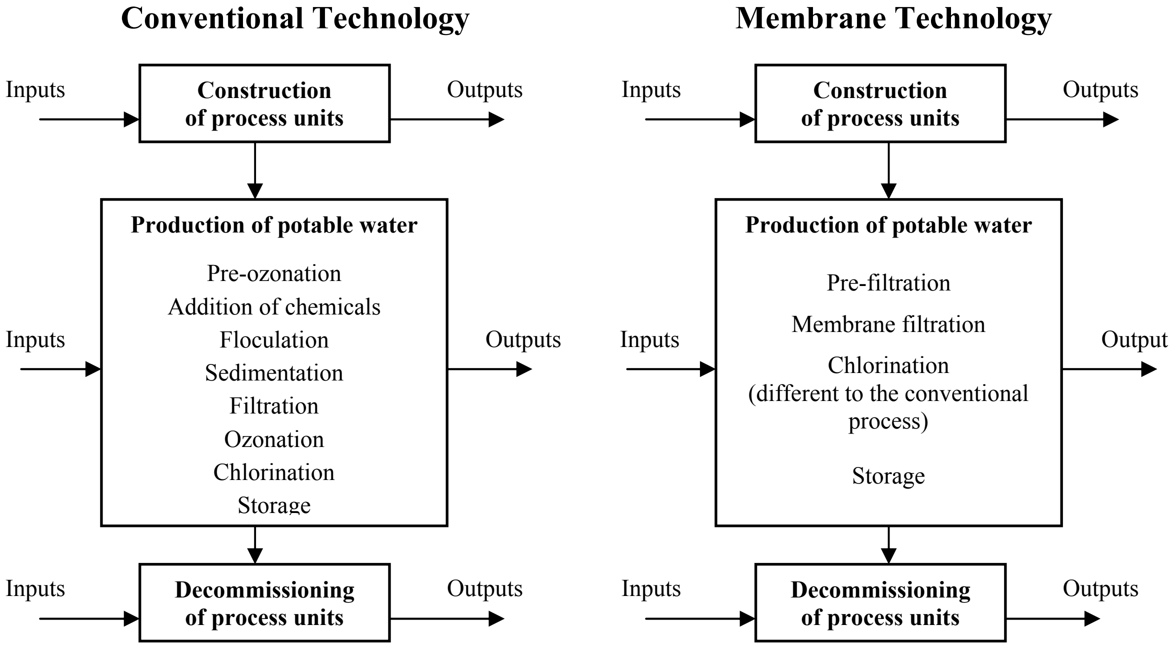


Figure 1: Framework for the LCA comparison

Usually at this stage, in this type of study, an LCA software package with inventory database and calculation facilities is used. For this project the GaBi 3 software was used. It contains data from two European databases: APME (Association of Plastic Manufactures in Europe) and BUWAL (Bundesamt fuer Umwelt, Wald und Landschaft – the Swiss Environmental Protection Agency) plus some data on processes from the IKP (Institut fuer Kunststoffkunde und Kunststoffprueffung) University of Stuttgart, the initial developers of the software. Therefore, this study is based on primary data collected directly from manufacturers, on secondary data obtained from the GaBi 3 database, and on tertiary calculated data.

All the inputs and outputs from all the processes included in the system are related to the functional unit and together they form the inventory list for that particular system. This inventory list is the input to the next phase of the LCA, which is the impact assessment.

The impact assessment phase is also called the evaluation (or valuation) phase in the literature and it relates the outcome of an inventory to the relevant environmental impact categories. The aim of this phase is to evaluate the significance of the impacts resulting from the inputs and outputs summarised in the inventory list. Category definition, classification and characterisation are the three mandatory steps for this phase according to the ISO documents. The impact categories (or environmental themes) considered in the literature are resource consumption (renewable and nonrenewable), global warming, ozone depletion, acidification, nutrification, photochemical oxidant formation, ecotoxicity and human toxicity. In the category definition step an array of impact categories should be chosen in accordance with the goal and scope of the study. The next step is classification and in this step all the inputs and outputs from the inventory list will be assigned to the chosen environmental categories. The third step is the characterisation and in this step all the entries for an environmental theme are multiplied by a scientifically determined weight factor. For example, for the impact category of global warming studies show that in a 100 year period 1 g of methane is 25 times more active than 1 g of carbon dioxide; and 1 g of nitrous oxides is 320 times more active than 1 g of carbon dioxide. Therefore, for this category all gases emitted will be multiplied by an equivalency factor expressing the gases' effect relative to that of carbon dioxide. All contributions to this environmental impact category are summed and expressed as carbon dioxide equivalents. At the end of the classification and characterisation steps each environmental impact category will have a score, and all the scores for all the impact categories considered will make up the environmental profile for a product (service or activity).

For this study the CML (Center for Environmental Science – University of Leiden, The Netherlands) method was used to perform the classification and characterisation steps. According to this method each chemical substance included in the inventory was assigned to an environmental impact category and multiplied by an equivalency factor. For the conventional technology there were 268 chemical substances summed in the inventory and for the membrane technology 254. All these entries could then be reduced to nine impact category scores as presented in the results section.

The above-presented method was developed in the northern hemisphere and in the local context it has some shortcomings. For example, in South Africa water is in limited supply compared to countries in Europe. However, in existing LCA databases and inventories it is seen as just another renewable resource and not even included in some data sets since it is not of importance for the original developer. These shortcomings have to be addressed in order to make LCA more efficient and meaningful in the local context.

The *interpretation* is the last phase of an LCA and the aim of this phase is to reduce the amount of data gathered during the LCA study to a number of key issues which will be usable in a decision making process. An improvement assessment is usually included with the conclusions and recommendations. This assessment considers scenarios for increasing the overall environmental performance of the system based on the findings of the LCA study.

Applications of LCA

A series of applications have emerged for LCAs, the most important ones being the calculation and comparison of environmental burdens, the use for product development and improvement, as a strategic planning and policy decision tool and in areas of ecolabelling, green procurement, waste management and marketing.

The number of LCA applications and the number of users have increased with the development and popularisation of LCA methodologies. Four types of primary users have been distinguished: industry and other types of commercial enterprises; national governments and local, national and inter-governmental regulative bodies; non-governmental organisations (NGOs) such as consumer organisations and environmental groups; and consumers, including governments as consumers (UNEP, 1996).

In the different applications three different levels of sophistication of the LCA have been distinguished. The conceptual LCA or the life cycle thinking is the simplest type of LCA, and companies employ it mostly internally. The simplified LCA focuses on the most important environmental aspects in a system and there is a strong international movement towards the standardisation of this type of study. The detailed LCA studies are the most time and data intensive studies, however their results are of higher quality. An LCA project has to match the goal of the study with the degree of detail required and obtainable.

In South Africa the drivers for LCA studies are less in number and by variations resulting in a more limited number of applications. However, this situation is expected to change since the demand for LCA type of studies is increasing. The increase in the number and quality of such studies is due to the fact that environmental LCA information is needed for international trade and specifically for products exported to developed countries. Since water is a primary commodity used for the production of most goods and in South Africa it is a scarce resource, it is important to present the environmental profile of potable water as calculated by an LCA to have a holistic view of all the environmental impacts due to obtaining potable water.

Limits and Constraints of LCA

There are two types of problems and limitations facing the South African LCA researcher. The first set is made up by limitations and problems related to the LCAs in general and the second set to problems specific for the local context.

The general limitations of LCAs are due to the methodological framework of this environmental tool and the simplifications used. For example, critical loads (or thresholds) as well as geographical or temporal considerations with regard to emissions are not taken into consideration and the LCA methodology calculates all emissions at the same time and in the same space assuming that all produce the worst case scenario. Other general problems of LCAs have been highlighted in three major areas: data gaps, data quality and methodological value choices. Some of these problems are in the process of being addressed (i.e. data gaps and data quality), however, others are far from being resolved (i.e. a unified methodology for toxicity or allocation).

South African limitations include the problems associated with adapting this tool to the local environment by including environmental problems specific to this part of the world. Most important in this area is the lack of assessment methodologies for water consumption and salination. The lack of critical review capacity is another local problem as well as the lack of local, specific LCA data. For example, electricity is one of the major inputs in this study and the local information on electricity generation was incomplete. Therefore, European data had to be used for this process.

Results and Discussions

By performing the phases described in the previous section environmental scores were calculated for both technologies used for the production of potable water. This study is a comparative one and common aspects such as the delivery of raw water to the waterworks and the storage of treated water have not been included in these scores.

Environmental Scores for the Conventional Technology

An inventory table was produced for the conventional technology used in the production of potable water taking into account the three life stages for a waterworks (i.e. construction, operation and decommissioning). With regard to the inputs, the first two impact categories considered are resource consumption and energy consumption and **Table 1** presents the values for this technology.

Table 1. Material and energy consumption for the conventional technology

Stage	***Material Consumption (kg/kL)***	***Energy Consumption (MJ/kL)***
Construction	0.0515	0.0873
Operation	2.7000	2.0670
Decommissioning	0.0002	0.0015
Total	**2.6515**	**2.1552**

The operation stage carries the highest burden with regard to material and energy consumption and the decommissioning stage the lowest. With regard to the outputs, by using the data gathered and the LCA methodology as presented in the previous section, the environmental profile for the conventional technology was calculated. This environmental profile is presented in **Table 2.**

Table 2. The overall environmental profile for the production of potable water by the conventional technology (worst case scenario)

Impact Category	*Score*	*Unit*
Global warming potential	1.85E-01	kg CO_2 equivalents
Ozone depletion potential	3.61E-09	kg CFC-11 equivalents
Acidification potential	1.10E-03	kg SO_2 equivalents
Eutrophication potential	7.40E-05	kg Phosphate equivalents
Photo-oxidant formation potential	1.57E-05	kg Ethene equivalents
Aquatic ecotoxicity potential	2.73E-03	kg DCB* equivalents
Terrestrial ecotoxicity potential	2.59E-01	kg DCB equivalents
Human toxicity potential	4.09E-03	kg DCB equivalents

**DCB is 1, 4 dichlorobenzene*

The overall 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 operation units. The proportion of individual stages to the overall score is presented in **Table 3**.

Table 3. Proportion of individual stages to overall score (worst case scenario)

Impact Category	*Construction (%)*	*Operation (%)*	*Decommissioning (%)*
Global warming potential	6.2	93.7	0.1
Ozone depletion potential	10.8	88.9	0.3
Acidification potential	7.1	92.9	0.0
Eutrophication potential	11.4	88.5	0.1
Photo-oxidant formation potential	15.8	83.9	0.4
Aquatic ecotoxicity potential	2.3	97.7	0.1
Terrestrial ecotoxicity potential	10.6	89.2	0.2
Human toxicity potential	18.1	81.0	0.9

As can be seen from **Table 3**, the operation stage dominates the life cycle for the conventional technology of producing potable water. The processes considered for this stage when modelling the environmental burdens are presented in **Fig. 2**.

The thickness of the arrows in **Fig. 2** is proportional to the quantity of mass transferred from one process to another (kg/kL). For energy flows (electricity and steam) this is not the case and energy flows were recorded in MJ/kL. The origin of the data used is presented in the left upper corner of each process box in **Fig. 2**. SA stands for South Africa, RER and EU for two European databases and DE for Germany.

All processes presented in **Fig. 2** are traced to the interface between the system (technosphere) and the environment (biosphere). It includes the extraction of raw materials on the input side and the production of useful substances and of emissions on the output side. As can be seen from the above figure, some inputs (e.g. chlorine) are used directly in the production of potable water but also indirectly for the production of other chemicals which enter the system.

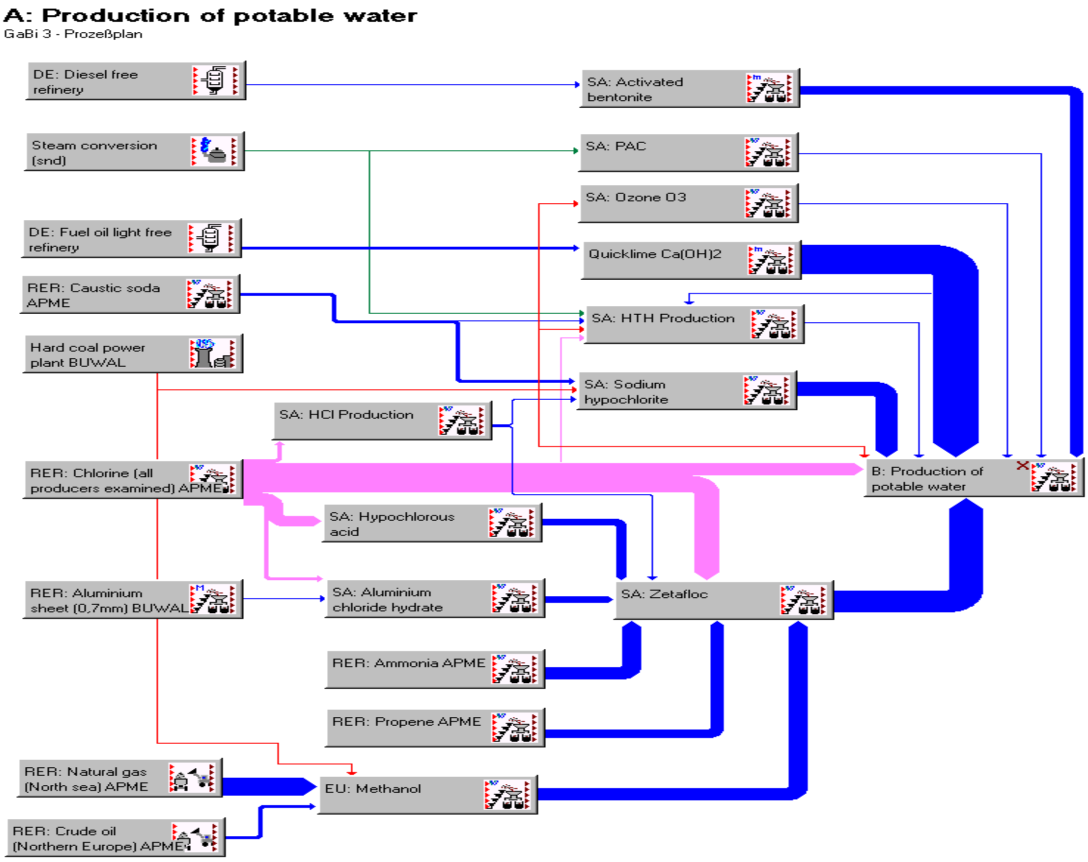


Figure 2: GaBi 3 process plan for the conventional technology

The majority of environmental burdens from the system presented in **Fig. 2** can be traced to one single process, namely the generation of electricity. This process has the highest contribution to all environmental categories considered. An illustration for the environmental impact category of global warming is presented in **Fig. 3**.

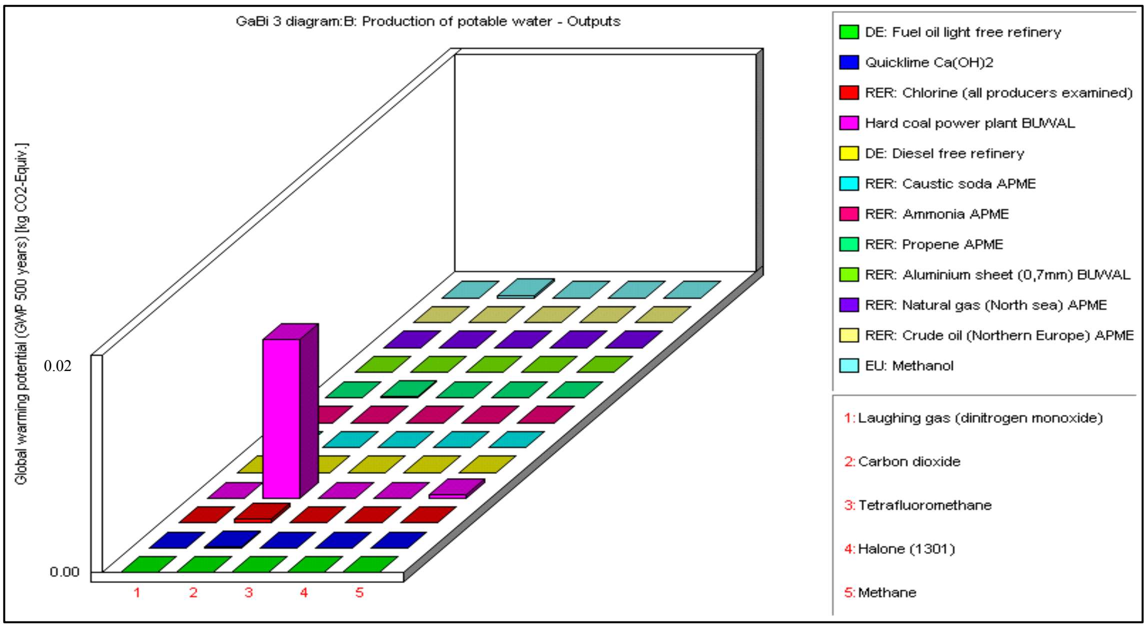


Figure 3: Contributors to global warming in the operation stage (conventional technology)

This is an example of the focusing capacities of the LCA environmental tool and it shows how the environmental burdens of a complex system can be traced to a limited number of processes which then have to be targeted for improvement. Therefore, for the conventional technology of producing potable water, increasing the energy efficiency of ozonation and sludge disposal, the two most energy (i.e. electricity) intensive processes will bring about measurable improvement of the environmental performance of the overall system.

Environmental Scores for the Membrane Technology

For this technology of producing potable water eight different design scenarios were investigated. In a similar fashion, an environmental profile was produced for all eight scenarios of the membrane case (Friedrich, 2001). The energy and resource consumption (inputs) associated with this technology is presented in **Table 4** for the worst scenario of the eight.

Table 4. Material and energy consumption for the membrane technology (worst case scenario)

Stage	***Material Consumption (kg/kL)***	***Energy Consumption (MJ/kL)***
Construction	0.0329	0.0557
Operation	2.5000	2.5900
Decommissioning	0.0004	0.0036
Total	**2.5333**	**2.6493**

Table 5 presents the environmental scores related to the outputs from this technology for the worst case scenario. Similar to the conventional technology the environmental burdens of the membrane technology are traced to the operation stage and to the generation of electricity used in this stage.

Table 5. The overall environmental profile for the production of potable water by the membrane technology (worst case scenario)

Impact Category	***Score***	***Unit***
Global warming potential	2.90E-01	kg CO_2 equivalents
Ozone depletion potential	9.55E-10	kg CFC-11 equivalents
Acidification potential	1.82E-03	kg SO_2 equivalents
Eutrophication potential	5.69E-05	kg Phosphate equivalents
Photo-oxidant formation potential	4.87E-06	kg Ethene equivalents
Aquatic ecotoxicity potential	2.11E-04	kg DCB* equivalents
Terrestrial ecotoxicity potential	7.79E-01	kg DCB equivalents
Human toxicity potential	1.78E-03	kg DCB equivalents

**DCB is 1, 4 dichlorobenzene*

Eight different design scenarios were considered for the membrane technology because the South African membrane method is still under development and the inclusion of environmental concerns at this stage allows for design improvements. The design option with the lowest electricity consumption had the lowest environmental scores. The most important areas for improvement were singled out as being the pressure and flowrate of the feed to the filtration modules and the efficiency of pumping.

Comparison of the two technologies for the production of potable water

With regard to inputs, the two technologies of producing potable water are compared in **Table 6**.

Table 6. Material and energy consumption for the two technologies

Stage	*Mass (kg/kL)*		*Energy (MJ/kL)*	
	Conventional Technology	**Membrane Technology**	**Conventional Technology**	**Membrane Technology**
Construction	0.0514	0.0329	0.0873	0.0557
Operation	2.6000	2.5000	2.0670	2.5900
Decommissioning	0.0001	0.0004	0.0009	0.0036
Total	**2.6515**	**2.5333**	**2.1552**	**2.6493**

For both technologies, the operation stage is the most energy and material intensive stage in the life cycle. The figures for material and energy consumption for both technologies are comparable, with the conventional technology having a slightly higher mass consumption and the membrane technology having higher energy consumption.

With regard to the outputs, the two technologies of producing potable water were compared by using the environmental profiles of the two systems and **Table 7** presents this comparison.

As **Table 7** above shows, for some impact categories (global warming, acidification and terrestrial ecotoxicity) the conventional technology scores better; for the rest of the categories the membrane technology has better scores. The environmental impact category with the closest scores for both technologies is eutrophication, and the impact category for which the scores vary most is aquatic ecotoxicity.

Table 7. Comparison of the environmental profiles for the two technologies

Environmental Impact Category	**Membrane Technology**	**Conventional Technology**	**Unit**
Global warming potential	2.90E-01	1.85E-01	kg CO_2-Equiv.
Ozone depletion potential	9.55E-10	3.61E-09	kg R11-Equiv.
Acidification potential	1.82E-03	1.10E-03	kg SO_2-Equiv.
Eutrophication potential	5.69E-05	7.40E-05	kg Phosphate–Equiv.
Photo-oxidant formation potential	4.87E-06	1.57E-05	kg Ethene-Equiv.
Aquatic ecotoxicity potential	2.11E-04	2.73E-03	kg DCB*-Equiv.
Terrestrial ecotoxicity potential	7.79E-01	2.59E-01	kg DCB-Equiv.
Human toxicity potential	1.78E-03	4.09E-03	kg DCB-Equiv.

**DCB is 1, 4 dichlorobenzene*

Sensitivity Analyses and Comparison with International Studies

Two sensitivity analyses have been performed in order to assess the sensitivity of the calculated environmental scores to the omission of transport and filtration nozzles. These analyses have proven that the difference of the scores is very small and therefore, the exclusion of transport and filtration nozzles is justified.

The results of this study have been compared to the results of other international studies undertaken in the water industry. In spite of the differences between these studies, a similar result pattern emerged, with the operation stage and the consumption of energy being identified as the major contributors to the environmental burdens of water treatment processes.

Conclusion and Recommendation

In conclusion, for both technologies of producing potable water, the life cycle is dominated by the operational stage. This stage has the highest material and energy consumption and the highest environmental scores for all the impact categories considered. The decommissioning stage is the least important one and the construction stage has an intermediate, but minor position. The most important process to which most of the environmental burdens for producing potable water are traced is the generation of electricity. This process dominates all environmental impact categories for the operation stage, for both technologies considered. Because of the predominance of the operation stage it dominates the entire life cycle for potable water production. The focusing capacities of this environmental tool are highlighted by these results, LCA being able to identify major environmental contributors in a complex, interconnected system. By targeting these major contributors, the overall environmental performance of the system can be improved in the most efficient manner. This case study in the application of LCA also demonstrates how this tool prevents the shifting of environmental burdens to different geographical locations. At the point of use electricity is seen as a *clean* power option, however, at point of generation there are emissions associated with this process, and these emissions are included in an LCA.

Since the majority of environmental burdens for producing potable water are traced back to the consumption of electricity for the operation of waterworks, the main recommendation emerging from this study is the need to increase electricity efficiency during operation. For the conventional technology as employed by Wiggins Waterworks, a first step towards better use of electricity would be monitoring and targeting electricity consumption. The next step would be to optimise all processes (starting with the most electricity consuming ones) and make them more energy efficient. For the membrane plant, choosing a design option which has the lowest electricity consumption is the most important step which should be undertaken. Efficiency of pumping is an issue which should be addressed, since it impacts the most on the overall electricity consumption. Also the pressures (ultrafiltration pressure, pressure drop, etc.) should be optimised further since they determine pumping needs. A further improvement can be made by designing the ultrafiltration modules for recycling (i.e. the materials making up the modules should be separated to enable recycling). However, compared with energy efficiency this is a minor improvement. A compromise between membrane hardware (capital) and energy consumption (operating costs) needs to be undertaken for using both financial and environmental considerations in guiding the development of the South African membrane technology.

In this study the main difficulties were experienced in the data gathering stage and they have been overcome by employing overseas data and by using calculations. These difficulties were related to the lack of availability of local data; however, with more demand for LCA studies in South Africa more data will become available and further LCA studies should be easier to undertake.

Technology Transfer Actions and Capacity Building

The educational aspect of this work has to be highlighted, because through interaction especially in the data-gathering phase, the concept of life cycle assessment and the basic methodology was introduced to a broad spectrum of people. This included technical staff at Wiggins Waterworks and in the following companies: Natal Portland Cement, ARCH Chemicals, Zetachem, Natal Plastics, Fedgas, Polifin, Eskom, Transnet, SMX Explosives and Shell S.A.

An academic seminar on this topic was give to the staff and postgraduates students in the Department of Chemical Engineering, University of Natal and a presentation of the final results of this research was given to Umgeni Water head office personnel.

Following list of academic publications resulted from this research:

1. Friedrich, E. and Buckley, C.A., 2000, The Application of Life Cycle Assessment (LCA) for the Production of Potable Water – A Case Study, BioY2K Combined Millennium Meeting, Rhodes University, Grahamstown, RSA, 23-28 January 2000 (Poster)

2. Friedrich, E., Wenzel, H. and Buckley, C.A., 2000, Life Cycle Assessment: National and International Experiences with a New Tool for Environmental Optimisation – A Case Study on Water Treatment Technologies, The Water Institute of South Africa (WISA 2000) Biennial Conference and Exhibition, Sun City, RSA, 28 May – 1 June 2000 (Paper and Oral Presentation)

3. Buckley, C.A., Wenzel, H. and Friedrich, E., 2000, Life Cycle Assessment - A Comprehensive Tool for Environmental Management, One Day Pre-Conference Workshop held at WISA 2000 Biennial Conference and Exhibition, Sun City, RSA, 28 May – 1 June 2000 (Workshop)

4. Friedrich, E. and Buckley, C.A., 2000, The Use of Life Cycle Assessment in Comparing Two Water Treatment Methods for the Production of Potable Water, The South African Institute of Chemical Engineers (SAIChE 2000) 9th National Meeting, Secunda, RSA, 9 – 12 October 2000 (Paper and Oral Presentation)

5. Friedrich, E., Buckley, C.A. and Jacobs, 2001, The Application of Life Cycle Assessment for the Production of Potable Water – A Case Study of Membrane Technology, 4th WISA-MTD Symposium on Membranes Science and Technology, Stellenbosch, RSA, 26 – 27 March 2001 (Paper – Best Oral Presentation)

6. Friedrich, E. and Buckley, C.A., 2001, Life Cycle Assessment as an Environmental Tool – A South African Case Study for the Production of Potable Water, International Association for Impact Assessment South Africa, Conference on Sustainable Relationships for a Sustainable Environment, White River Mpumalanga, RSA, 8 –10 October 2001 (Paper and Oral Presentation)

7. Friedrich, E. and Buckley, C.A., 2001, Life Cycle Assessment as an Environmental Management Tool in the Production of Potable Water, International Water Association Conference on Water and Wastewater Management for Developing Countries, Kuala Lumpur, Malaysia, 29 – 31 October 2001 (Paper and Oral Presentation)

As a result of the current research two more LCA projects have been launched. The first one involves a full gate-to-gate LCA for two paper products produced by Mondi Ltd. It is an engineering masters project funded by Mondi Ltd. and the NRF (National Research Foundation). The second project is a smaller in-house project by Natal Portland Cement in which the collection of data for cement production was extended for two more years in order to calculate better environmental burdens for their cement products. The Pollution Research Group assisted with checking the calculations done. The Pollution Research Group also assisted Enviroserv, an environmental consultancy, in undertaking LCAs for two products (one cosmetic and one shoe polish brand). Umgeni Water expressed interest in taking the LCA further in their organisation by extending the study done on Wiggins Waterworks to other waterworks and by initialising an energy saving campaign.

Capacity building occurred through building expertise in undertaking LCAs. There were consultative interactions between this project and the Mondi LCA project and between this project and the two different projects run by industry (Natal Portland Cement and Ecoserv). One workshop was organised in collaboration with the WISA 2000 conference and contributed to the popularisation of LCAs in South Africa. By the interactions in the data collection stage, LCAs were introduced to a large number of people from different companies. These interactions are essential in creating awareness about LCAs and setting the scene for further capacity building.

Achievement of Project Aims

As can be seen from the results and discussions presented, the aims of this research project as stated in the introductory section have been achieved. The environmental profiles for two water treatment technologies have been calculated and they show the life cycle environmental consequences of these technologies. Recommendations for the improvement of the total environmental performance of selected water treatment processes are provided. This research is a case study for the application of LCA in the South African water industry and as such it shows some of the benefits of incorporating LCA methodologies in this industry.

The aim of this study with regard to alerting the water industry to the benefits of using LCAs was fulfilled through the technology transfer actions presented in the previous section. Not only the water industry was alerted to these benefits but a much wider audience including other industries and academia.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission and entitled:

THE USE OF LIFE CYCLE ASSESSMENT IN THE SELECTION OF WATER TREATMENT PROCESSES

The Steering Committee responsible for this project, consisted of the following persons:

Dr N Mjoli	Water Research Commission (Chairman)
Dr L J du Preez	Water Research Commission (Secretary)
Mrs E J Engels	Water Research Commission (Secretary)
Mr G Steenveld	Water Research Commission
Mr P Thompson	Umgeni Water
Ms L Boyd	Department of Water Affairs and Forestry
Prof FAO Otieno	University of Durban Westville
Mr C Olivier	Durban Metro – Water Services
Mr B Atkinson	Technikon Natal
Dr E Jacobs	University of Stellenbosch
Ms A Haasbroek	ISCOR
Ms J van der Walt	SASOL

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged gratefully.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record sincere thanks to the following:

Prof H Wenzel	Danish Technical University
Prof M Overcash	University of North Carolina
Umgeni Water	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

APME	Association of Plastic Manufacturers in Europe
BS	British Standard
BUWAL	Bundesamt fuer Umwelt, Wald und Landschaft, Switzerland
CFC	Chlorofluorocarbons
CML	Center for Environmental Science, University of Leiden, The Netherlands
DAF	Dissolved Air Flotation
DCB	1, 4 Dichlorobenzene
DE	Germany
EDIP	Environmental Design of Industrial Products
EF	Equivalency Factors
EIA	Environmental Impact Assessment
EMAS	Eco-Management and Audit Scheme (EU)
EPA	Environmental Protection Agency (USA)
EPS	Environmental Priority System
EU	European Union
HTH	Calcium Hypochlorite
IKP	Institut fuer Kunststoffkunde und Kunststoffprueffung, University of Stuttgart
IPCC	Intergovernmental Panel on Climatic Change
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LC_{50}	Lethal Concentration for 50% of the organisms in a test
NASA	National Aeronautics and Space Administration (USA)
NEP	Nordic Environmental Sound Product Development
NGO	Non-governmental Organisation
NOAA	National Oceanic and Atmospheric Administration (USA)
NOEC	No Observed Effect Concentration
OD	Outer Diameter
PE	Polyethylene
PEMS	Pira’s Environmental Management System
PLA	Product Line Analysis
POCP	Photochemical Ozone Creation Potential
polyDADMAC	Poly-diallyldimethylammonium Chloride
PVC	Polyvinyl Chloride
REPA	Resource and Environmental Profile Analysis

RER	Country Code for Europe in the SPOLD System
SA	South Africa
SABS	South African Bureau of Standards
SETAC	Society of Environmental Toxicology and Chemistry
SPOLD	Society for the Promotion of Life Cycle Assessment Development
THM	Trihalogenated Methane
UCT	University of Cape Town
UKDoE	United Kingdom Department of Environment
UNEP	United Nation Environmental Programme
USA	United States of America
USES	Uniform System for the Evaluation of Substances
VOC	Volatile Organic Compounds
WCED	World Commission on Environment and Development (UN)
WMO	World Meteorological Organisation

CHAPTER 1
INTRODUCTION

This chapter serves to introduce this project by setting the scene for this study. The project aims, outputs and approach are discussed and an outline of the remainder of the report is provided.

1.1 Introduction to the Study

In the context of sustainable development, life-cycle assessment (LCA) is emerging as one of the tools of cleaner production. It is the only tool which has a cradle-to-grave approach and by this it provides a holistic view with regard to the environmental burdens due to a product (service or activity). The LCA methodology enables the calculation of environmental burdens in a systematic and scientific way by regarding all the inputs and outputs of a system. Hence, it allows for comparison on environmental grounds between two systems performing the same function. Due to these unique characteristics, in this study, this tool was used to assess the environmental burdens resulting from the production of potable water and to compare the environmental burdens of two different water treatment technologies.

In South Africa potable water is one of the most valuable resources and as a result much work has gone into establishing and achieving environmental quality in the process of obtaining this water. Each of the individual processes used in the production of potable water has associated environmental burdens. This study compares the environmental burdens resulting from two different technologies used in the production of potable water in South Africa. The first one is the *conventional technology* and is currently employed at Wiggins Waterworks, a waterworks of Umgeni Water situated in Durban, South Africa. The main processes involved are preozonation, addition of chemicals, flocculation, sedimentation, filtration, ozonation, chlorination and storage. The second technology is based on the use of a South African *membrane filtration* technology, and the following processes are involved: prefiltration, membrane filtration, chlorination (different to the previous technology) and storage. There are three pilot plants employing this membrane technology in South Africa. For the conventional technology this LCA study identifies the main contributions to the overall burdens, focusing on areas for improvement. For the membrane technology of producing potable water this LCA study, besides identifying the main environmental contributions, may guide further development of the technology in order to improve its environmental performance.

The environmental impact categories, on which the environmental performance of the two technologies of producing potable water are compared, include global, regional and local impacts. The impact categories are enumerated as follows: global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity and human toxicity. An inventory of all inputs and outputs for the production of potable water by the two technologies was prepared. This was followed by a quantification of the contributions by the two technologies to each of the environmental impact categories. The inputs from processes involved in the production of water include energy inputs and raw material inputs. The outputs include products, by-products and emissions to air, water and soil. To relate the different life spans of the various inputs (e.g. tanks, pumps, and pipes) for the production of potable water as well as to allow comparison between the two technologies, a functional unit is used. For this study the functional unit is the production of 1 kL of water to the quality specified by Umgeni Water for potable water produced over the life period of a process unit at a capacity of about 200 ML/day.

Formal LCA methodologies (as presented in the ISO 14040 series of standards) guided this study and these methodologies produce a score for each environmental theme. The methodologies involved and the results obtained are presented and the environmental performances for each of the impact categories are compared for the two technologies. Areas of intervention for environmental improvement have been detected and measures for improvement are recommended.

1.2 The Objectives and Aims of the Study

The overall objective of this study is to generate information on the environmental life cycle of water treatment processes used in the production of potable water. The specific aims of the study are defined as follows:

- to improve the total environmental performance of selected water treatment processes,
- to guide designers and owners of water on the full life cycle environmental consequences of selected treatment processes,
- to alert the water industry to the benefits of using full life cycle assessment in the selection of processes, and
- to develop capacity in undertaking life cycle assessments.

Therefore the specific objectives of the study are:

- to conduct life cycle assessments for one conventional and one membrane water treatment technology, and
- to compare the environmental burdens associated with each process.

1.3 Research Products

This project envisaged following research products:

- a quantification of the environmental burdens due to the production of potable water by using different processes,
- a comparison of two different technologies to produce potable water,
- recommendations for the improvement of the environmental performance of the processes studied, and
- a case study for the application of LCA in the water industry in South Africa.

The target groups for these products are water authorities, environmental planners, waterworks design engineers, developers and researchers of membrane systems, government departments and agencies, policy makes, industry and students.

1.4 Project Approach

An extensive literature review was undertaken as part of this project in order to establish the theoretical framework and the paradigm in which the concept and the methodologies of LCA were developed as well as to collect information about LCA (definitions, history, development, methodologies, etc.).

A series of local and international contacts have been established with other researchers and organisations involved in the field of LCA. International contacts include Prof. Henrik Wenzel (Danish Technical University, Denmark), Prof. Michael Overcash (University of North Carolina, USA) and Dr. Sven Lund (University of New South Wales, Australia). National contacts include researchers from Sasol, CSIR, University of Cape Town (UCT), Impala Ltd. and Eskom. The international contacts were essential for the facilitation of transfer of technology and some data. The national contacts are helping in developing a common approach to South African problems and limitations.

Two technologies of producing potable water were chosen, taking into account the representativeness of each technology for the processes employed in South Africa. The collection of data focussed on the processes making up these two technologies and on the requirements of the LCA tool employed.

This LCA study was guided by the ISO 14040 series of standards, which set the steps to be followed. In the calculation of environmental scores the CML (Center for Environmental Science – University of Leiden) methodology was followed.

1.5 Report Outline

Following the introduction, **Chapter 2** gives the background to environmental life cycle assessment. It briefly presents the paradigm in which it emerged, followed by the definition, history, applications and limitations of environmental life cycle assessments. The background information on processes used for the two technologies involved in producing potable water is provided in **Chapter 3**. **Chapter 4** highlights the different stages of this study and the methodologies associated with each stage. Assumptions and limitations are also presented as well as problems encountered in the research process. **Chapter 5** presents the research results and provides a discussion of these results for each of the two technologies investigated. A comparison of the results from the two technologies is also presented. **Chapter 6** is the concluding chapter and summarises the findings of this research and provides recommendations to improve the environmental performance for the production of potable water.

CHAPTER 2
BACKGROUND TO LIFE CYCLE ASSESSMENT

A literature review was undertaken as part of this project and this chapter summarises and highlights the main sources used in order to give a background to the concepts and methods employed in this study.

2.1 Life Cycle Assessment and Sustainable Development

Industrial growth is seen as the engine for economic development and an important component for the economic welfare of society, by providing employment and creating wealth. However, industry contributes to environmental degradation through the inputs and the outputs resulting from its functioning (Park and Labys, 1998). A variety of raw materials are used such as minerals, water, wood, fossil fuels etc., and the depletion of these resources can cause serious environmental problems. In addition industrial processes generate, besides useful products and by-products, emissions (gaseous, liquid and solid) to air, water bodies and soil. In response to these environmental problems the concept of sustainable development emerged. Sustainable development was defined as: *development which meets the needs of the present generation without compromising the ability of future generations to meet their own needs* (Our Common Future, 1987) by the United Nations World Commission on Environment and Development. Another United Nations initiative, the Rio Summit focused on the goals of sustainable development and through its subsequent treaties directed the practical implementation of this concept. Agenda 21, the most important international initiative emerging from the Rio Summit, provides a list of activities for the implementation of sustainable development. One of the most important paths set for industry to implement sustainable development is centered around the concept of cleaner production. Cleaner production is defined as

> *the continuous application of an integrated preventative environmental strategy applied to processes and services to increase overall efficiency and reduce risks to humans and the environment.*
>
> - *Production processes: conserving raw materials and energy, eliminating toxic raw materials, and reducing the quantity and toxicity of all emissions and wastes.*
> - *Product: reducing negative impacts along the life cycle of a product, from raw materials extraction to its ultimate disposal.*
> - *Services: incorporating environmental concerns into designing and delivering services (UNEP Website).*

This definition underlines the importance of the life cycle of a product and the tool used to assess and improve the environmental performance in this context is the life cycle assessment. An LCA is a tool in which environmental burdens associated with a product (system or activity) are documented and evaluated by taking into account all the impacts due to the use of raw materials and all the emissions produced.

2.2 Definition of Environmental Life Cycle Assessment

A detailed LCA is a complex process and in the literature there are many definitions capturing one or more of its theoretical or methodological aspects. One of the most comprehensive definitions of LCA is proposed by Lindfors et al. (1995):

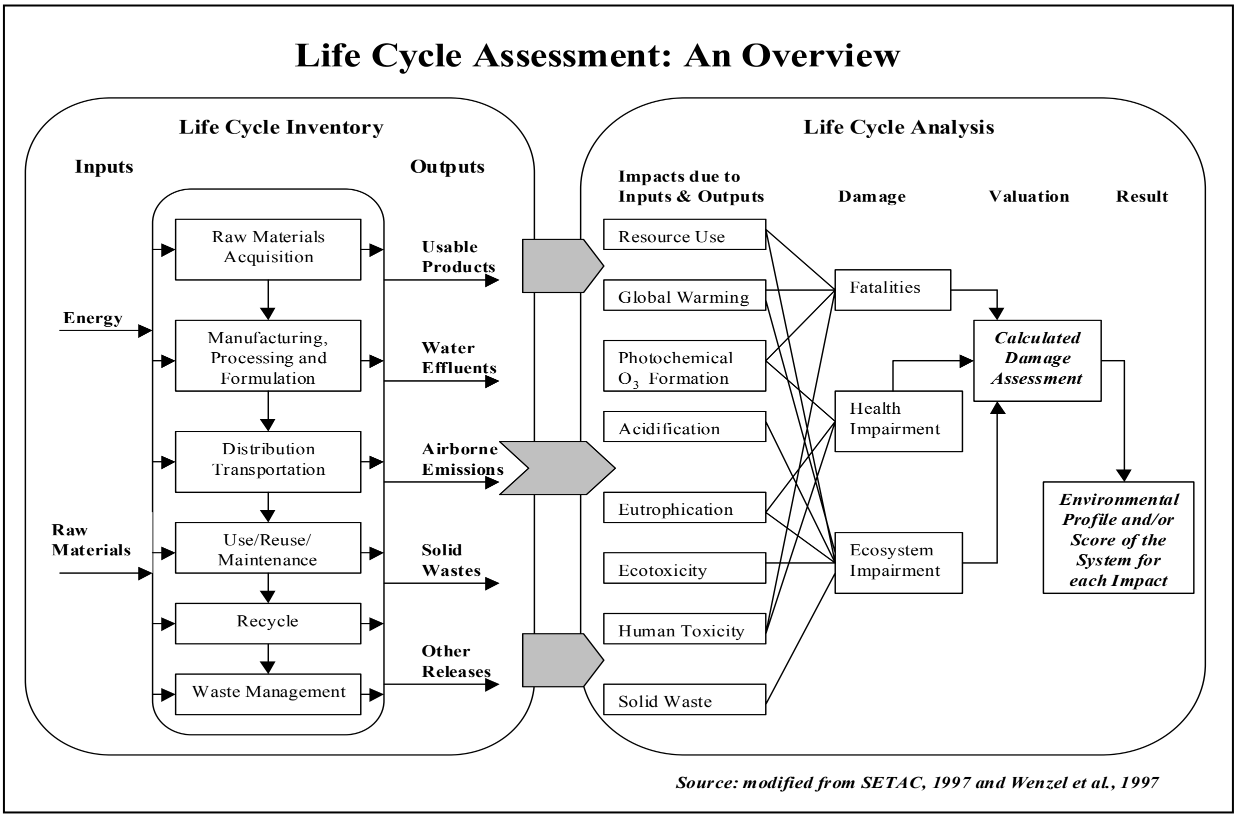
> *LCA is a process to evaluate the environmental burdens associated with a product system, or activity by identifying and quantitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of those energy and material uses and releases to the environment. The assessment includes the entire life cycle of the product or the activity, encompassing extracting and processing of raw materials; manufacturing; distribution; use; maintenance; recycling and final disposal;*

> *and all transportation involved. LCA addresses the environmental impacts of the system under study in the areas of ecological systems, human health and resource depletion. It does not address economic or social effects.*

In the South African Bureau of Standards (SABS) and the International Organisation for Standardisation (ISO) 14040 standard (1997), the definition of LCA is given as follows:

> *LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by*
>
> - *compiling an inventory of relevant inputs and outputs of a system,*
> - *evaluating the potential impacts associated with those inputs and outputs,*
> - *interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.*
>
> *LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health and ecological consequences.*

Fig. 2.1 presents a graphical representation of an overview of the LCA process.



Source: modified from SETAC, 1997 and Wenzel et al., 1997

Figure 2.1: Environmental life cycle assessment – an overview

2.3 History of Environmental Life Cycle Assessment

The early beginnings of modern LCA can be traced back to the 1960s and the studies of this period dealt with issues such as energy efficiency, consumption of raw materials and to a lesser degree with waste production or disposal of waste materials (Curran, 1996 and Weidema, 1997). The focus of these early studies was mainly on material inventory and therefore quantification was of great importance (material and energy balances).

In 1969 the Coca-Cola Company initiated and funded a study by the Midwest Research Institute to compare and determine which container had the lowest release to the environment and the lowest consumption of material resources (Weidema, 1997). The process of quantifying the resource use and the environmental release became known as Resource and Environmental Profile Analysis (REPA) and in the early 1970s a series of such studies were conducted in the USA and Europe. Especially energy studies gained momentum during this period because of the oil crisis. However, in the late 1970s and early 1980s interest in LCA type of studies declined and only a few specialists, mainly in the academic world, continued LCA activities (Kloepffer, 1997).

It was in the late 1980s with the growing environmental crisis that interest in LCA type of studies was revived, and since then the area of application of LCA has grown continuously, including industries, planners, design establishments, government agencies, retailers, consumers, etc. It was at the beginning of this revival stage when different LCA methodologies were developed, and focus was shifted beyond compiling inventories to include more detailed analyses of impacts and potential impacts due to resource consumption and the emissions produced (Weidema, 1997). Quantification was and still is important and it continues to grow, especially with the development and release of the first extensive databases, which were made publicly available (the first one (BUWAL) in Switzerland in 1984). Parallel to the quantitative inventory approach, a broader qualitative tradition developed in Germany under the name *Produkt-Linien-Analyse* (Product Line Analysis or PLA). PLA is considered to be an ambitious approach because it includes a comprehensive choice of parameters including social and economical aspects (Weidema, 1997).

In the 1990s, a series of national projects were initiated in order to develop consistent and simple methods, especially for product development. These initiatives are: the product ecology project (Sweden) leading to the EPS (Environmental Priority System) method, the United States Environmental Protection Agency (US EPA) life cycle design project, the NEP (Nordic Environmental Sound Product Development) project in Norway and Sweden, the National Reuse of Waste Research Programme (NOH) methodology in the Netherlands and the Environmental Design of Industrial Products (EDIP) project in Denmark (Weidema, 1997). This evolution, together with the growing number of practitioners, lead to a rapid diversification of the LCA methodology to the point where different studies for the same product gave different results because of different methodologies. In this context it become obvious that the LCA had to be standardised and by the mid 1990s a series of guidelines were produced, like SETACs *Code of Practice* (Consoli et al.,1993), *US EPA Guidelines* (Vigon et al., 1993) and the *Nordic Guidelines on Life-Cycle Assessment* (Lindfors et al., 1995).

The Society of Environmental Toxicology and Chemistry (SETAC) and especially its European branch shaped the development of LCA through a series of workshops and publications which in the early 1990s set the conceptual and methodological basis for the LCA structure. This structure was further refined and improved by work done for the Nordic Council of Ministers, individual contributions from different research centers and universities, work for the International Organisation for Standardisation (ISO), especially the ISO 14040 series and the Society for the Promotion of Life Cycle Assessment Development (SPOLD). Of special importance are the ISO 14040 series of LCA standards since they are based on widespread consensus from within the LCA community.

2.4 Overview of the Life Cycle Assessment Methodology

Over time different ways of conducting LCAs and different levels of sophistication of the LCA methodology have emerged. This section is a brief overview of the main steps to be undertaken in an LCA study. A more detailed overview is presented in Friedrich (2001) including the ISO

14040 methodological framework. ISO 14040 (1997) sets the four phases, which have to be part of a LCA as follows: goal and scope definition, inventory analysis, impact assessment, and interpretation. Each of these four phases will be briefly presented.

2.4.1 Goal and Scope of the Study

The first step in an LCA study is the goal and scope definition. Defining the **goal** of the study should address issues like intended applications, reasons for doing the study and the intended audience. In addition, the initiator should be mentioned (Heijungs et al., 1992). Under **scope** of the study the ISO documents recommend the following issues be considered and defined: the function of the product system, or, in the case of comparative studies, the systems; the functional unit; the product systems boundaries; allocation procedures; data requirements; assumptions; limitations; type of critical review, if any; and type and format of the report required for the study. From this array of issues special attention has to be given to the functional unit. The functional unit of this study is defined as 1 000 kg of potable water at the quality stipulated in the Umgeni Water guidelines (see Friedrich, 2001 Appendix 2) produced over the life period of a process unit at a capacity of about 200 ML/day. The system boundaries are another important issue and decisions on what should be included and what should be excluded will influence data collection. In the literature (Lindfors et al., 1995; Wenzel et al., 1998, and others) there are a series of cut-off rules and they all include a certain degree of subjectivity.

2.4.2 Inventory Analysis

The **inventory analysis** involves data collection and calculation procedures to quantify relevant inputs and outputs of a process. **Fig. 2.2** presents the main steps involved in producing an LCA inventory.

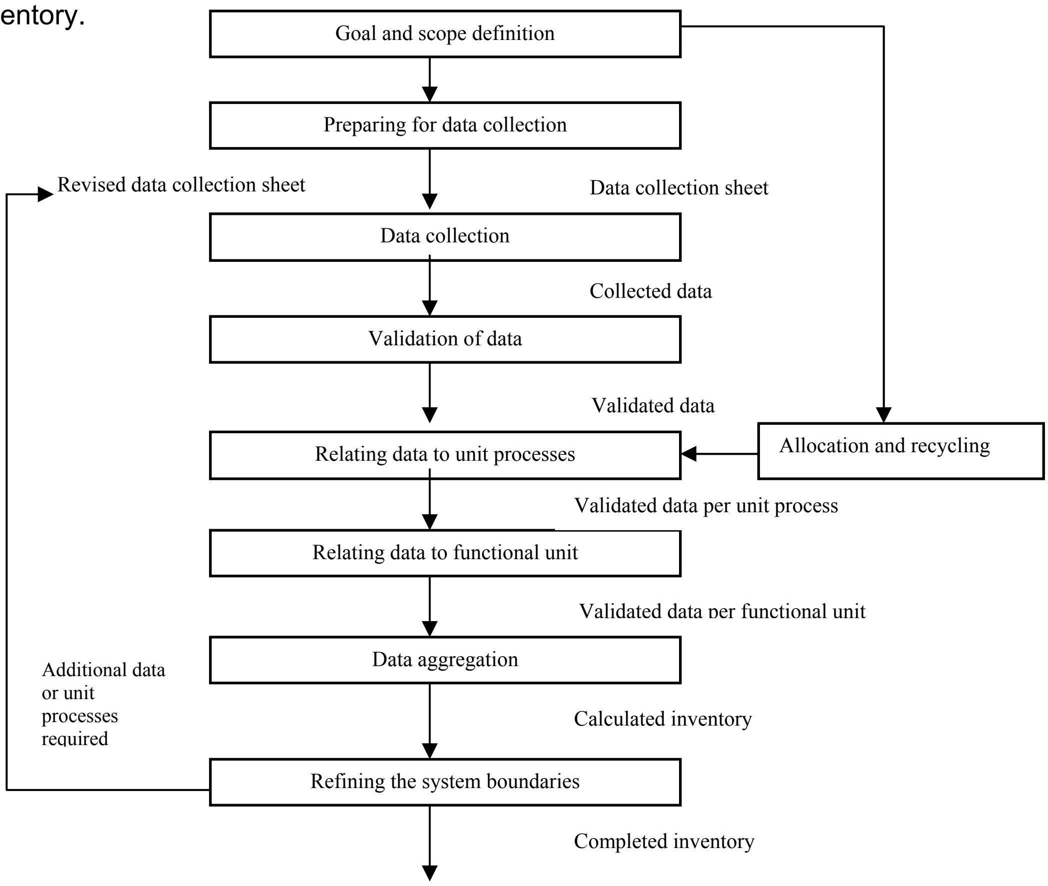


Figure 2.2: Simplified procedures for the inventory analysis (source: ISO 14041)

For each of the processes included in the system all the process inputs and process outputs have to be established and quantified. If quantitative data are not obtainable for some of the processes in the system then qualitative data have to be used. For very detailed studies site specific data are sought, however, in most cases regional or country specific data are considered good enough. More general data can be obtained from trade organisations, public surveys, manufacturers associations, etc., and in reality most of the studies published so far use a combination of site specific and general data.

Usually at this stage, in this type of study, an LCA software package with an inventory database and calculation facilities is employed. For this project the GABI 3 software was used. It contains data from two European databases: APME (Association of Plastic Manufactures in Europe) and BUWAL (Bundesamt fuer Umwelt, Wald und Landschaft – the Swiss Environmental Protection Agency) plus some data on processes from the IKP (Institut fuer Kunststoffkunde und Kunststoffprueffung) University of Stuttgart, the initial developers.

All the inputs and outputs from all the processes included in the system are related to the functional unit and together they form the inventory list for that particular system. This inventory list is the input to the next phase of the LCA, which is the impact assessment.

2.4.3 Impact Assessment

The **impact assessment** is the third phase of an LCA and its aim is to evaluate the significance of the potential impacts resulting from the inputs and outputs summarised in the inventory list. It is also aimed at reducing the complexity and volume of the inventory data by translating these data into contributions to relevant environmental problems. The following elements are considered mandatory for this phase: selection of impact categories, category indicators and characterisation models (also referred to as category definition); assignments of inventory results to the impact category (classification) and calculation of category indicator results (characterisation). Optional elements are normalisation (calculation of the magnitude of category indicators results relative to reference information), grouping, weighting and data quality analysis. Another term used in the literature for weighting is valuation and in some studies normalisation is merged with valuation.

i) *Category definition* involves establishing the environmental impact themes for the study. Therefore, it states the environmental problems towards which the contributions from a system should be investigated. These 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.

The most important impact categories used in the literature are as follows:
- abiotic resource consumption,
- biotic resource consumption
- global warming potential,
- stratospheric ozone depletion potential,
- photochemical oxidant formation potential (sometimes called smog 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 and the software employed 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.

ii) *Classification* is the process by which inventory input and output data are assigned to the categories chosen. Some of the outputs (e.g. NO_X) contribute to more than one category and therefore such outputs have to be counted for each category once. Double or triple counting is acceptable if the effects are independent of each other, whereas double counting of different effects in the same effect chain (e.g. stratospheric ozone depletion and toxicological effects like skin cancer) is not permitted. Formal rules exist for the different methods.

iii) The aim of the *characterisation* process is to aggregate all the effects in a particular impact category in order to obtain a single score. For this purpose characterisation factors are used. These factors have been derived scientifically and may change with scientific progress. For example, suppose that in the impact category global warming there are two substances (carbon dioxide and nitrous oxide) contributing to this effect. Scientifically it was established that for a timeframe of 100 years, 1 kg of nitrous oxide will produce an effect 310 times higher than 1 kg of carbon dioxide (Hauschild and Wenzel, 1998). Therefore, 1 kg of nitrous oxide will produce an effect equal to 310 carbon dioxide equivalents and the characterisation factor is 310. Once all substances in the category of global warming are expressed as carbon dioxide equivalents (the reference substance), these can be summed up resulting in a single score for global warming. All the impact categories use characterisation (or equivalency) factors. For most of the impact categories there is consensus regarding the characterisation step, with the exception of human and ecological toxicity, biotic resource consumption and land use.

All the scores from all the categories considered make up the environmental profile of the system or product studied. Different environmental profiles obtained through the same methodology can be compared on the basis of environmental criteria.

2.4.4 Interpretation

Interpretation is the fourth phase in life cycle assessment. 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.

Interpretation is performed in interaction with the three other phases of the LCA. If the results of these previous phases are not good enough to match the goal and scope as set at the beginning of the study, then improvements are needed. The three principal steps of the interpretation according to the ISO 14043 standard are: identification of the significant issues based on the inventory and the impact assessment phases of the LCA, evaluation (completeness, sensitivity and consistency checks) and conclusions, recommendations and reporting.

2.5 Applications of LCA

A series of applications have emerged for LCAs and Jensen et al. (1997) present some of these emerging application as follows:

- internal industrial use for product development and improvement,
- internal strategic planning and policy decision tool in industry,
- external industrial use for marketing purposes, and
- governmental policy making in areas of ecolabelling, green procurement and waste management opportunities.

The number of LCA applications and the number of users has increased with the development and popularisation of LCA methodologies. Four types of primary users have been distinguished: industry and other types of commercial enterprises; national governments and local, national and inter-governmental regulative bodies; NGOs such as consumer organisations and environmental groups; and consumers, including governments as consumers (UNEP, 1996).

Jensen et al. (1997) distinguishes three different levels of sophistication of LCA for the different applications. These levels are: the conceptual LCA or life cycle thinking, the simplified (or streamlined LCA) and the academic, detailed LCA. Much of the efforts to develop and standardise LCA methodologies have been applied to the detailed studies. Recently, however, a definite trend towards simplification has been observed.

The **conceptual LCA or life cycle thinking** is the first and most simple type of LCA. It is usually based on qualitative information or on simple scoring systems. This type of LCA is suited to a basic environmental understanding of the life cycle of the product or system under consideration. Although most are not published, conceptual LCAs are useful in-house environmental tools, since they bring environmental aspects into the day to day functioning of companies and show employees the potential environmental consequences of their decisions and actions.

The **simplified LCA** is defined as the application of the LCA methodology for a comprehensive screening assessment (i.e. covering the entire life cycle superficially or covering it fully but using qualitative and/or quantitative generic data). For this type of exercise standard modules for transportation and/or energy production, followed by a simplified impact assessment are used. A simplified impact assessment may focus on the most important environmental aspects, on potential environmental impacts, on stages of the lifecycle, on phases of the LCA, or on any combination of these four possibilities. These type of studies usually need a thorough assessment of the reliability of the results (Christiansen, 1997). The rational beyond simplifying is to obtain the same results as a detailed LCA but in a shorter time and with less data and/or expense. This would make implementation of LCA concepts more efficient and straightforward in practice (Graedel, 1998), and widen the areas where LCAs can be applied. Greadel (1998) presents extensive examples on how different companies and some academia went about simplifying LCAs. In all these examples researchers are trying to preserve the LCA concept and rigour sufficiently to inspire confidence in the results, while at the same time meeting the scientific and logistical constraints that are inevitably present with simplification (Graedel, 1998). The results of most of these simplification techniques are in the form of a matrix, with one axis being the life cycle stages and the other one a list of environmental and health and safety impacts. Since the benefits of simplified LCA are obvious in terms of time and costs, there is a strong international movement (SETAC and ISO) towards standardising the simplification process in order to make it more reliable.

A **detailed LCA** is an application of the LCA methodology for a detailed, quantitative and mostly system-specific study. Simple cut-off or allocation rules are not acceptable (Christiansen, 1997). Therefore, the detailed LCA is the most data intensive and time consuming approach and traditionally it is the only one accepted as a real, academic LCA. However, some of the applications of LCAs do not require such a high level of detail and a successful LCA project will have to match the goal of the study with the degree of detail required and obtainable.

2.6 Applications of LCA in South Africa

The range of applications of the LCA methodology in South Africa varies from the applications seen overseas. **Table 2.1** presents some of the applications presented in the literature and highlights which of them are currently used in South Africa.

The difference in applications in South Africa as compared to overseas is due to the internal use of LCA by the different companies and due to the fact that there is no pressure in South Africa to publish LCA data. Therefore, for companies conducting LCA studies, it is a voluntary exercise motivated mainly by the internal benefits they see arising from such studies.

Table 2.1. Some of the applications for LCA and the level of detail required

Application overseas	Application in RSA	Most used level of detail in LCA		
		Conceptual	Simplified	Detailed
Generation of environmental profiles	SASOL, ISCOR, ESKOM, Impala Platinum Ltd., Mondi Paper		x	**X**
Design for Environment	SASOL	x	**X**	x
Product development	Not applied	x	**X**	x
Product improvement	Not applied		**X**	x
Environmental claims (ISO type II-labelling)	Not applied	x		
Ecolabelling (ISO type II-labelling)	Not applied		**X**	
Environmental declaration (ISO type III-labelling)	Not applied		**X**	x
Organisation marketing	Not applied		**X**	x
Strategic planning	SASOL	x	**X**	
Green procurement	Not applied	x	**X**	
Deposit/refund schemes	Not applied		**X**	
Environmental (green) taxes	Not applied		**X**	
Choice between packing systems	CSIR	x		**X**

"X" in bold and upper case indicates the most frequently used level

Source: modified after Jensen et al., 1997

The above mentioned motives explain why the first application for LCA in South African companies is the generation of an environmental profile, in other words the generation of information on the environmental burdens of the products produced. The second application mentioned, which is used as frequently as the first one, is using LCA to support other environmental initiatives - most often ISO 14001 environmental management systems. This application is based on the focusing capacities of the LCA methodology. For example, for a particular product an LCA can identify the highest contributor to the total environmental burden and determine the cause (process or stream) of this contribution. By focusing environmental efforts, like the ISO 14001 environmental management systems, towards addressing the cause, the best possible environmental improvement is obtainable. The same mechanism is employed in the third application mentioned by South African companies, namely for supporting internal waste minimisation projects. Other applications mentioned are strategic environmental assessment, environmental impact assessment support, environmental reporting and design for the environment. Only the SASOL team has employed these last four applications. A number of applications, which are listed in the overseas literature, are not used in South Africa.

The drivers for LCA studies are less in number and by variation in South Africa than in countries in Europe, Japan or the USA, resulting in a limited number of applications. However, there has been an increased demand for South African LCA data from overseas, as many of the products exported from South Africa go to countries where the demand for environmental data is high and where environmental burdens of products are criteria for choosing (or not choosing) a product. This external driver will probably result in many more LCA studies being conducted by companies and it is expected that the use of LCAs will increase.

The information presented on the South African applications was collected through the interaction with most of the LCA practitioners in South Africa. This exchange of information was facilitated by the creation of the South African LCA network in December 1999. The creation of this network was the initiative of the Pollution Research Group, University of Natal, and it was the first time that South African organisations and people with interests in LCA came together.

2.7 Limits and Constraints of LCAs

Besides the unique advantages of LCA there are shortcomings and limitations which have to be understood and considered when applying it. There are two types of limitations and problems facing South African LCA researchers. The first set is made up by limitations and problems related to the LCA tool and its methodological framework in general, and the second set of problems is specific for the South African setting.

2.7.1 General Limitations and Constraints

LCA, as any other environmental tool, tries to convey a complex real life situation or system into a number of parameters, using different simplifications in the process. Part of the limitations of LCA originate from this simplification process and it has become clear that *experience has introduced caution in some previous thinking that LCA could be a complete or comprehensive assessment* (Owens, 1999). The most vehement critics argue that comprehensive comparison or the determination of environmental superiority using life cycle impact assessment is not a realistic expectation due to three main reasons. First, it is believed that LCAs cannot cover all issues or every part of complex industrial systems and, therefore, LCAs will always be incomplete in some way. Second, critics argue that it does not address absolute considerations since it uses potential environmental impacts which are calculated as opposed to actual environmental impacts which are measured. Thirdly, it is believed that gaps and omissions in inventory data and lack of resolution and environmental representativeness in life cycle impact assessment methods are inevitable to some degree now and in the future (SETAC, 1997 in Owens, 1999).

Finnveden (2000) reviewed some of the current LCA studies and of some of the databases available. This review produced the following observations:

- energy inputs are included in most cases without major gaps,
- other raw materials are included but with severe data gaps,
- water is not included in most cases,
- land use, habitat alterations and impacts on biodiversity are in most cases not included. These categories will continue to pose a methodological problem, since there is no agreement on how to consider them in an inventory analysis,
- toxicological impacts on humans and on ecosystems are often included, but with severe data gaps. It is estimated that these impacts will never be fully described without data gaps, because of the sheer number of chemicals used in society and the lack of knowledge on the behaviour of these chemicals,
- non-toxicological human impacts and impacts in the working environment are lacking,
- impacts like global warming, ozone depletion, acidification, eutrophication and photo-oxidant formation are fairly well covered, however, there are shortcomings. Most notably data on

eutrophication of aquatic systems is usually incomplete (due to insufficient data for water emissions) and data for organic compounds contributing towards photo-oxidant formation is expressed as a general parameter (e.g. particulate emission) making differentiation impossible.

The variation in quality of the existing data is another shortcoming according to Finnveden (2000). He cites a comparison of different databases for PVC and concludes that uncertainties can be quite large, often an order of magnitude or larger (Finnveden, 2000). This variability is explained by different methods of allocation and different technology levels sometimes existing in the same country at the same time. Therefore, a careful selection of data for the appropriate technology may improve the quality of a study. In time, problems associated with data gaps and data quality will be reduced with the development of better databases and the collection of more data.

Forbes (1999) and Owens (1997) present a series of other limitations in current LCA methodology. These are related to the fact that the LCA methodology does not consider thresholds and spatial and temporal circumstances. For most environmental impacts, the relationship between the dose of pollutant and the effects caused is not necessarily linear and critical loads or thresholds exist. Critical loads or thresholds imply that below a certain dose of pollutant an ecosystem has the capacity to remove it efficiently. Critical loads are specific for each ecosystem and because of that it is impossible to incorporate the concept in a general LCA model or method. The emissions, as calculated by the LCA methodology and presented in an LCA inventory, do not occur all at the same place and at the same time. Current LCA methodologies assume that all emissions occur at sensitive sites and that all emissions cause effects, presenting by this the worst case scenario regarding emissions (Forbes, 1999).

The uncertainties associated with the methodology for the inventory and the impact assessment phase are related to processes in which different value choices are introduced. Most notably, allocation (see Friedrich, 2001, Appendix 1, for the theoretical background on allocation) is one of these processes and Finnveden (2000) argues that multi-input allocation may be difficult to solve even if there is agreement on the guiding principles. A classical example illustrating this point is an incinerator of municipal waste, which receives a multitude of wastes and produces a number of pollutants. If one has to allocate the dioxins to the different inputs, two methods are available. In the first method dioxins are allocated according to the chlorine content of the input and in the second method they are allocated according to carbon content (or calorific value). Both methods are based on the guiding principle of natural science based causality, both are equally valid, however, they produce totally different results. Since the formation mechanism of dioxins is not well understood (Wikstrom et al., 1996 in Finnveden 2000), the only criteria for choosing between these methods is the suitability with regard to the scope and goal of the study. This suitability has to be decided by the researcher on no real scientific grounds. As a result, it must be acknowledged that methodological choices introduce uncertainty in the results and that these choices are influenced by culture, frames and paradigms (Finnveden, 2000). One way to overcome this problem is standardisation (Consoli et al., 1993 and ISO 14040, 1997).

LCA relies on other scientific disciplines for data and methodologies like, for example, toxicology, climatology, chemistry etc. If science does not provide the answers to certain questions (e.g. the mechanism for the formation of dioxins is not known) it is clear that this will impose limitations on LCAs depending on this data. However, this is a problem shared by all other environmental tools.

In summary, LCA has a series of shortcomings and limitations, most notably related to data gaps, data quality and value-choices. In spite of these limitations, this tool is valuable because of its unique *cradle-to-grave* approach, which makes it irreplaceable by any other tool.

2.7.2 South African Limitations and Constraints

Data availability and quality is a common problem for the studies done by academia and research institutes so far in South Africa. With regard to availability of data, there is a general reluctance by South African companies to provide input data for LCA studies. This reluctance may be explained by the fact that managers in different companies are not sensitised to LCA and the data requirements of this method. Therefore, few companies have data in the format that can be used in an LCA and usually it is time and effort consuming to compile this data. Another factor, which may explain the reluctance of companies to release environmental data, is historical and originates from the high protectionism South African companies enjoyed in the past.

All the commercial LCA software tools and databases have been developed overseas and present the LCA researcher with the problem of applying the data collected elsewhere to the South African situation. This can introduce a margin of error, because data between countries and continents differ due to different factors, in particular different technologies and regulations. However, because of the lack of data for South Africa, LCA practitioners in this country do not have any option other than to use overseas data. Similar problems are faced not only by South Africa, but also by some of the developed countries.

Another major problem, which is specific to South Africa, is the relevance to this country of the assessment step in the LCA methodology. The impact categories in which environmental effects are categorised (e.g. global warming, stratospheric ozone depletion, human and ecotoxicological impacts, acidification, eutrophication, etc.) have been developed for the European and the USA situation. Impacts considered not important in the Northern Hemisphere are of major importance for this country. For example, South Africa is a water scarce country, consequently water, as a resource, is very important. However, although there is a growing acceptance that there is a global water and water quality shortage, this is not reflected in the established LCA methodology. The same is valid for water salination and soil erosion. Therefore, there is a need to adapt the methodology to include local environmental priorities and small steps are being taken in this direction.

A further South African problem is the lack of critical review capacity in South Africa. It is important to have a critical review for any study, which is designed to be published. Because the LCA community in South Africa is small and most of the studies done were for internal consumption, the critical review step was not performed very often. However, with the increasing use of LCA, the need for critical reviewers is increasing.

In spite of these limitations it is expected that the demand for LCA type of studies will grow in South Africa. This development is predicted because environmental LCA information is required in order to access export markets in most of the developed countries. Not only the quantity but also the quality of these studies is expected to rise since they will have to comply with international standards. It is believed that if South African products are to be marketed internationally and specifically exported to first world countries, *LCAs need to be performed as prescribed, for example, by EU legislation, the international customer, etc.* (Stinnes et al., 1996). Therefore it is important to draw attention to the environmental problems specific to this country and to incorporate them in the LCA methodology.

CHAPTER 3
BACKGROUND TO WATER TREATMENT PROCESSES

This chapter introduces two different technologies for producing potable water. The first one is the *conventional technology* and it is currently employed at Wiggins Waterworks, a waterworks of Umgeni Water situated in Durban. The second technology is based on the use of *membrane ultrafiltration* and currently a pilot study using this technology is taking place at Wiggins Waterworks in collaboration with the Water Technology Group (Dr. Pillay), ML Sultan Technikon and the Institute of Polymer Science (Dr. Jacobs), University of Stellenbosch.

A framework for the comparison of these two technologies taking into account the three main life cycle stages of a waterworks and the processes for each technology is presented in **Fig. 3.1**.

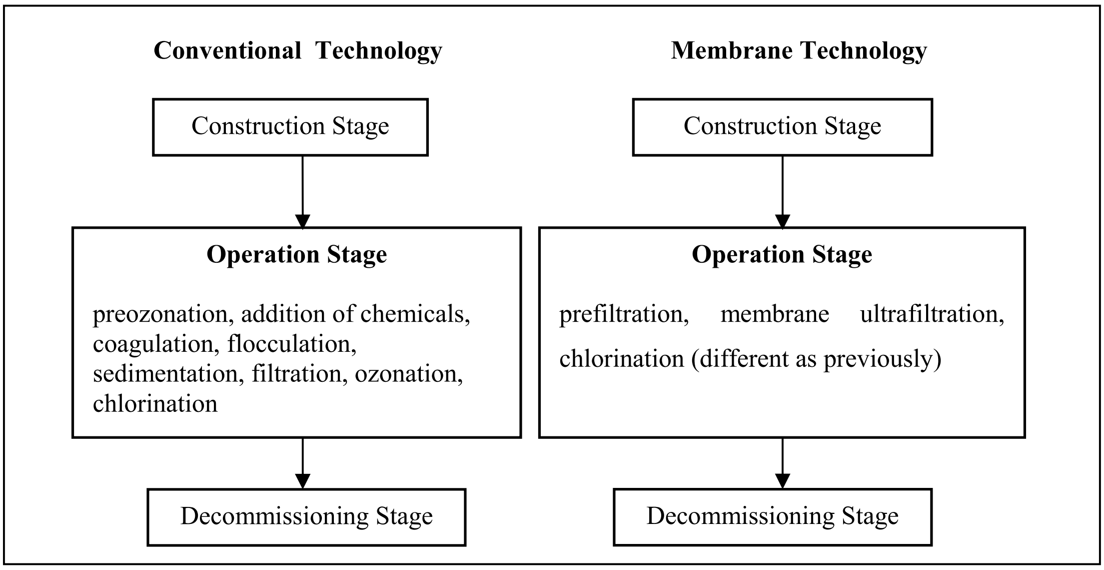
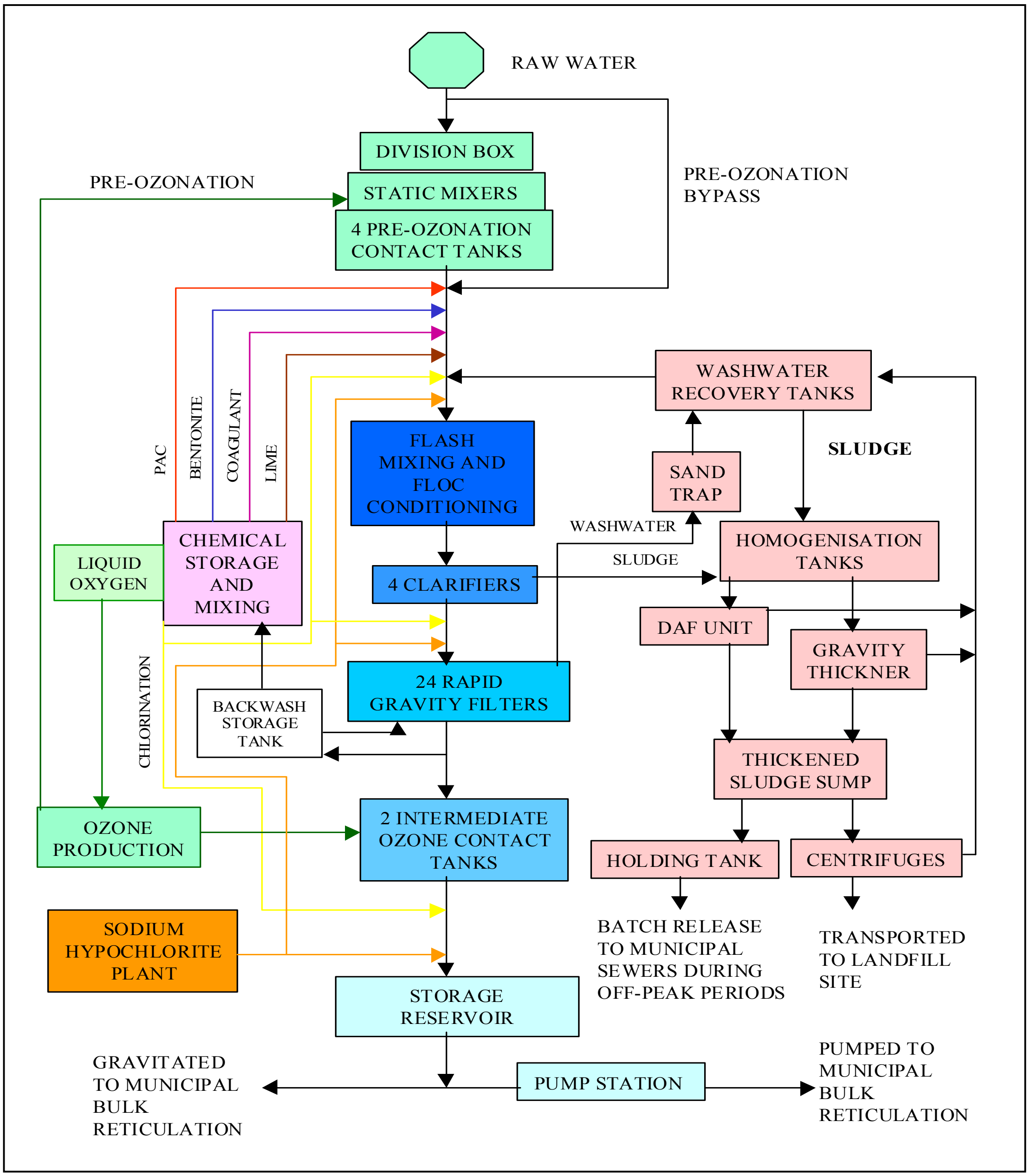


Figure 3.1: Comparison of two technologies for producing potable water

3.1 The Conventional Technology (Wiggins Waterworks)

Wiggins Waterworks is one of the eleven waterworks of Umgeni Water. It is situated in the Durban Metropolitan Region in the area of Cato Manor. This waterworks was commissioned in August 1984 and the initial capacity was 175 ML/day. In 1995, following an expansion, this capacity was raised to 350 ML/day, but during the study period an average of about 200 ML/day potable water was produced. 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 raw water enters the waterworks through the intake tower and flows through an aeration tank. The tower eliminates surges in the waterflow and the aeration tank is only operated when necessary. After the aeration tank, the water passes through a covered concrete channel into a pre-ozonation tank. The addition of chemicals follows the pre-ozonation operation and dosing facilities exist for lime, polymeric coagulant, bentonite, sodium hypochlorite, chlorine and powdered activated carbon (PAC). Passing the water over weirs enhances the mixing of water and chemicals. The water then flows into 4 banks of pulsator clarifiers. The clarified water is directed into 24 rapid gravity filters after which it is passed through the intermediate ozonation tank. It is chlorinated before flowing into two storage reservoirs from where it is distributed. The sludge from the clarifiers is directed to the homogenisation tank after which it enters the sludge plant. The washwater from the filters is directed through a sand trap to the washwater recovery tanks from where the clear water is recycled to the head of the waterworks and the settled solids are pumped to the homogenisation tank (Mr. Thompson, personal communication, 1999). An illustration of the overall process is presented in **Fig. 3.2** and more details are presented in Friedrich (2001).



Source: Umgeni Water's Public Affairs Department

Figure 3.2: Process flow chart for the conventional technology

Each step in the treatment of water is monitored via a computer system. The quality of water is monitored at the beginning of the works when it is still raw water, after the chemical additions, after filtration and the final water is also checked. In-line pH, turbidity, dissolved oxygen and temperature meters monitor raw water quality. Since the quality of incoming water varies widely, additional facilities exist at the head of the works (before pre-ozonation) to dose powdered activated carbon, bentonite and chlorine (as gas or as sodium hypochlorite) in order to deal with low quality incoming water.

3.2 The Membrane Technology

In order to compare the environmental burdens resulting from the conventional process employed at Wiggins Waterworks with a membrane process producing the same quantity of potable water of the same quality, a virtual membrane plant had to be designed. This design was based on the information gathered from the membrane pilot plant situated at Wiggins Waterwoks.

3.2.1 Membrane Technology

The local capillary ultrafiltration membrane technology involved in this project has been documented in a series of publications such as Jacobs and Leukes (1996), Jacobs et al. (1997) and Pryor et al. (1998). So far this technology has been employed only on a small scale and in essence it is based on a low pressure (ultrafiltration) membrane operation. The capillary membranes used for the ultrafiltration pilot plant were manufactured by researchers at the Institute for Polymer Science, University of Stellenbosch, using a protocol documented by Jacobs and Leukes (1996). The polysulfone membranes have a well defined internal skin, but have no external skin. The microvoids in the membrane are narrow-bore and extend the full width of the membrane. The capillaries have an internal diameter of about 1.2 mm and an external diameter of about 1.9 mm. These membranes are cut to a given length, usually about 1.2 m and packed in netting covered bundles. The bundles are then inserted into a 90 mm PVC pipe forming a module. The ends of the modules are sealed off and at the same time the ends of the membranes are fixed, using a urethane-based epoxy which is poured into a mould and then centrifuged (Jacobs, 1999). The modules have seals for connection to the raw water supply. They also have a product outlet through which the filtered water exits the module.

The way the pilot plant at Wiggins Waterworks was operated is documented by Pryor et al. (1998) in the following few sentences.

> *Feed water is pumped through a strainer and pressure sand filter, which in the absence of coagulation and flocculation, serve as grit traps only. Recycle pumps circulate the water through the capillaries, thereby maintaining a maximum cross-flow velocity of 1 m/s and inducing sufficient shear to limit the deposition of material on the inside of the membranes. During normal operation, a positive displacement (product) pump is used to draw a constant flow of permeate through the membranes. The trans-membrane pressure was monitored and regular flow reversal was used as a backflush strategy to assist in limiting the fouling of the membrane surface*.

The same authors mention the need for regular cleaning-in-place operation and this is usually done when the trans-membrane pressure reaches levels of 80 to 100 kPa. For the membrane pilot plant at Wiggins, with water characterised by colloidal particles and low levels of organic carbon, a chlor-alkali (50 ppm sodium hypochlorite) solution is used for cleaning in place (CIP).

3.2.2 The Layout of the Membrane Plant

The three processes that are employed at the Wiggins membrane pilot plant are pre-filtration (with the help of rapid sand filters), membrane ultrafiltration (to eliminate undesired substances) and chlorination to prevent the re-inocculation of pathogens. These processes are presented in **Fig. 3.3**.

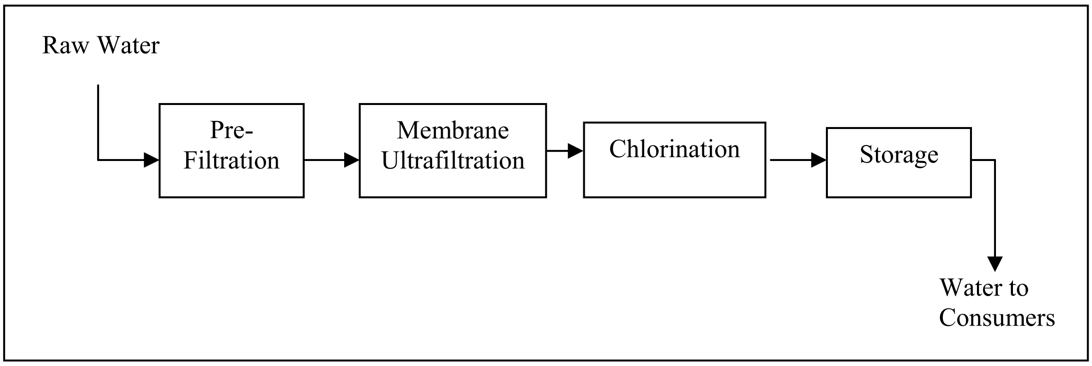


Figure 3.3: Diagram of the membrane technology

For the filtration process it has been assumed that a filtration unit exactly the same as the filtration unit in the conventional technology will be employed. For the chlorination process a dosage similar to the final dosage in the conventional technology has been assumed. The storage of the potable water resulting from this technology was assumed to be identical to the storage in the conventional technology.

3.2.3 Up-scaling the Membrane Pilot Plant

The basic unit of design of a membrane plant is a ultrafiltration module. There are several types of modules used for large-scale water treatment and they vary in: module dimensions, membrane material, pore size, capillary diameter, position (horizontal or vertical), inside-out or outside-in filtration and other specific characteristics like air-flushing, interchangeable membranes or submersible type membranes (Oosterom et al., 1998). The South African modules are vertically installed, with inside-out filtration and the membranes are not interchangeable. As presented above, the module used for this study consists of a PVC shroud, the membranes enclosed in a polyethylene netting, epoxy sealers (at both ends of the module), nitrile lip sealers and a product connector. Each of these components has been weighed for a 90 mm OD (outside diameter) shroud and upscaled to a 250 mm OD shroud, which is what would be used for a large scale plant. Data on how the membranes are produced and on how the modules are assembled have been collected from the Institute for Polymer Science, University of Stellenbosch. Data on how the modules are run in the pilot plant, as well as the different technical parameters for operation, have been collected from Mr. Moodley, ML Sultan Technikon. The technical specifications of a single original module used at the Wiggins Waterworks pilot plant are presented in **Table 3.1**.

For the planned large-scale plant a dead-end ultrafiltration process will be employed, therefore there will be no separate backflush line. To perform this operation at the same scale as Wiggins Waterworks (i.e. to purify about 200 000 kL/day) 1 620 to 4 740 modules are needed, depending on the size of the modules and the flux assumed during the operation stage. The modules can be arranged in different ways. For the purpose of this study batches of 30 and 60 modules were considered. In total eight different scenarios were used for calculation:

- short modules (1 250 mm), low flux (50 L/m^{2}h), banks of 30 and 60 modules,
- short modules (1 250 mm), high flux (100 L/m^{2}h), banks of 30 and 60 modules,

- long modules (1 600 mm), low flux (50 L/m^{2}h), banks of 30 and 60 modules, and
- long modules (1 600 mm), high flux (100 L/m^{2}h), banks of 30 and 60 modules.

New technical specification sheets have been calculated for all four types of modules (see Friedrich 2001, Appendix 5).

Table 3.1 Technical specifications of original membrane filtration modules

Dimensions	
Number of capillaries per module	6500
Diameter of capillary	0.0012 m
Filtration length of capillary (excludes epoxy moulded part)	1.08 m
Filtration area per capillary	0.0040 m^2
Filtration area per module	26.45 m^2
Cross-sectional flow area per capillary	1.13E-06 m^2
Cross-sectional flow area per module	0.0073 m^2
Conditions for ideal filtration	
Crossflow velocity through capillary	1 m/s
Feed pressure	1.5 Bar max
Assumed flux	50 L/m^{2}h
Assumed water recovery	95 %
Flowrates and Cleaning - in - Place (CIP)	
Permeate / product flowrate per module	1 322.56 L/h
Raw feed flowrate per module	1 392.18 L/h
Reject flowrate per module	69.61 L/h
Backflush flowrate per module*	69.61 L/h
Downtime duration per CIP	1.5 h
Assumed no. of CIP's over a 30 day period	2
Other downtime per 30 day period	10 h
Vol. of water required per module for CIP	262 L/CIP

**Observation: reject flow equals backflush flow for dead end filtration*

Membrane ultrafiltration modules are arranged in banks of modules (30 and 60 modules) and each bank is serviced by a supply and a product (or permeate) line. The supply line consists of small pipes, intermediary pipes and two large pipes. The small pipes are directly connected to the modules and the average length of small pipes was considered to be 0.2 m. The small pipes connect to intermediary pipes, which for the raw water supply line branch of from two big incoming pipes. The length of the intermediary pipes was assumed to be 7.5 m. After membrane filtration, the permeate is collected in another line namely the product line. This line also consists of small pipes, individual for each filtration module, and of modular intermediary pipes which then collect in two major pipes conducting the clean water to the storage facility. The same lengths were assumed for the small and intermediate pipes of the permeate line as for the pipes of the raw water supply line. For the large pipes (two for the supply line and two for the product line) an average length of 100 m was assumed. The sizes of the pipes were calculated using economical piping calculations based on the flowrates in these lines. The flows were different for the different scenarios considered. The material consumption for constructing these pipes was calculated by using data from pipe manufacturers expressed as kilogram material per meter of pipe for the required pipe thickness.

Thickness is dependent on the pressure of the water in the pipes and standardised schedules were obtained from pipe manufacturers. Similar engineering design calculations were done for pumps. For pumps, in addition to the pressure and the flow needed, efficiency calculations were included in order to approximate electricity consumption. Calculations on the pipes and pumps needed are presented in Friedrich (2001) (see Appendix 6). This appendix also presents a sample calculation for pipes and pumps.

CHAPTER 4
METHODOLOGY

This chapter defines the goal and scope of this study and presents the means and the stages used to achieve them. The general methodology used in this study follows the ISO standards procedural framework. This framework prescribes four steps to be undertaken: goal and scope definition, inventory analysis, impact assessment and interpretation. The methodology used for the impact assessment phase (or stage) uses the CML (Center for Environmental Science, University of Leiden) methodology for impact category definition, classification and characterisation

4.1 Goal and Scope Definition

The goal and scope definition is one of the most important steps in performing an LCA. This step defines the system to be studied, the reasons for performing the study and the breadth and depth of the study in relation to the reasons stated (Guinee et al., 1998). This step also fixes the objectives of an LCA, determining the potential applications of an LCA study and assessing for what it can and cannot be used for (Wenzel et al., 1997).

4.1.1 Defining the Goal of the Study

The ***goal*** of the study is to generate environmental information on the life cycle of water treatment processes, to identify the improvement potentials for these processes and to compare the environmental burden of a conventional water treatment process with that of a process involving membranes. Therefore, this study aims to:

- present designers and owners of water and wastewater treatment facilities with the life cycle environmental consequences of selected treatment technologies or processes,
- highlight areas for improvement of the environmental performance of selected water and wastewater treatment processes, and
- alert the water industry to the benefits of using full life cycle assessment in the selection of processes and technologies.

Therefore the objectives of the study, as presented in **Chapter 1** are:

- to conduct life cycle assessments for one conventional and one membrane water treatment technology,
- to compare the environmental burdens associated with each process, and
- to make the results and the methodology available to designers and owners of water and wastewater treatment facilities and to the water industry in general.

The ***intended audience*** or the target group for this study is made up of water authorities (in particular environmental and operational managers), engineers involved in designing new waterworks, scientists involved in the development of membrane technology, environmental authorities and environmental planners. In addition, LCA practitioners are expected to use this study since water is an input in most manufacturing processes.

The ***reasons*** for carrying out this study are primarily to generate LCA type of environmental information on the production of potable water. There is an increased demand for this type of information from other LCA practitioners, because water is an input in most industrial processes and, therefore, it is important to know the environmental consequences of producing this water. Another reason for performing this study is to compare a conventional technology for producing potable water with a membrane technology. Since the membrane technology is in development, the results of this study may influence and guide new developments in this area. These reasons explain why the Water Research Commission of South Africa funded this study.

4.1.2 Defining the Scope of the Study

The scope of the study should be *sufficiently well defined to ensure that the breadth, the depth and the detail of the study are compatible and sufficient to address the stated goal* (ISO 14040, 1997). Issues to be considered when defining the scope of the study are: the system under study with its functions and boundaries, the functional unit, allocation procedures of the environmental burdens for products and by-products resulting from the same process, data requirements, assumptions, limitations, type of critical review (if any) and type and format of the report for the study.

The ***systems*** under scrutiny in this study are the two technologies (conventional and membrane) for producing potable water. These two technologies have been described in **Chapter 3**. Both systems have one function, namely to produce potable water of a certain quality starting with raw water of identical quality. These quality specifications enable comparison on the base of the functional performance of the two systems.

The ***functional unit*** for this study is defined as follows: 1 kL of potable water at the quality stipulated in the Umgeni Water guidelines produced over the life period of a process unit having a capacity of about 200 ML/day. The functional unit is the unit to which all data collected in the inventory phase will be related and it will be the basis for comparison for the two technologies. All impact scores produced in the impact assessment phase of this LCA study will be expressed referring to the functional unit.

The ***boundaries*** of the two systems are presented in **Fig. 4.1** and **Fig. 4.2**. These figures show the processes included and also show the processes which have been excluded and considered to be unimportant to the comparison. Initially the transportation for all the processes was included, however, after collecting data for the first few processes (cement production and the production of sand and stone) it became obvious that transport was responsible for only a very small (in these cases insignificant) proportion of the environmental impacts. As a result it was decided to exclude transport and to perform a sensitivity analysis at the end of the study to justify this decision. Should the sensitivity analysis prove that for the overall system, transport is important, then it would be re-included. However, the sensitivity analyses proved that the exclusion was justified (see **Section 5.5**) for both systems. No other process was left out in the first iteration of this study and all direct inputs for both the technologies have been included. However, due to the lack of data some second and third degree processes (i.e. processes used in production of the raw materials used for producing the direct inputs) were left out. The exclusion of these processes was considered acceptable due to their small contribution to the function of the system, as expressed in terms of the functional unit. In general, the contribution of these inputs was in the order of a few nanograms per kilolitre of potable water produced.

Allocation of environmental burdens (resource consumption and emissions) to products and by-products resulting from the same industrial process is a debated issue in LCA. A series of methods have been used (LCA-NORDIC, Technical Reports No 1-9, 1995), but all of these methods have shortcomings. For this study, the production of potable water process does not need allocation, since there are no by-products; however, the production processes for many of the inputs (e.g. chlorine) require allocation, since a series of by-products result from the production process. In accordance to the precautionary principle, worst case scenarios have been used for and

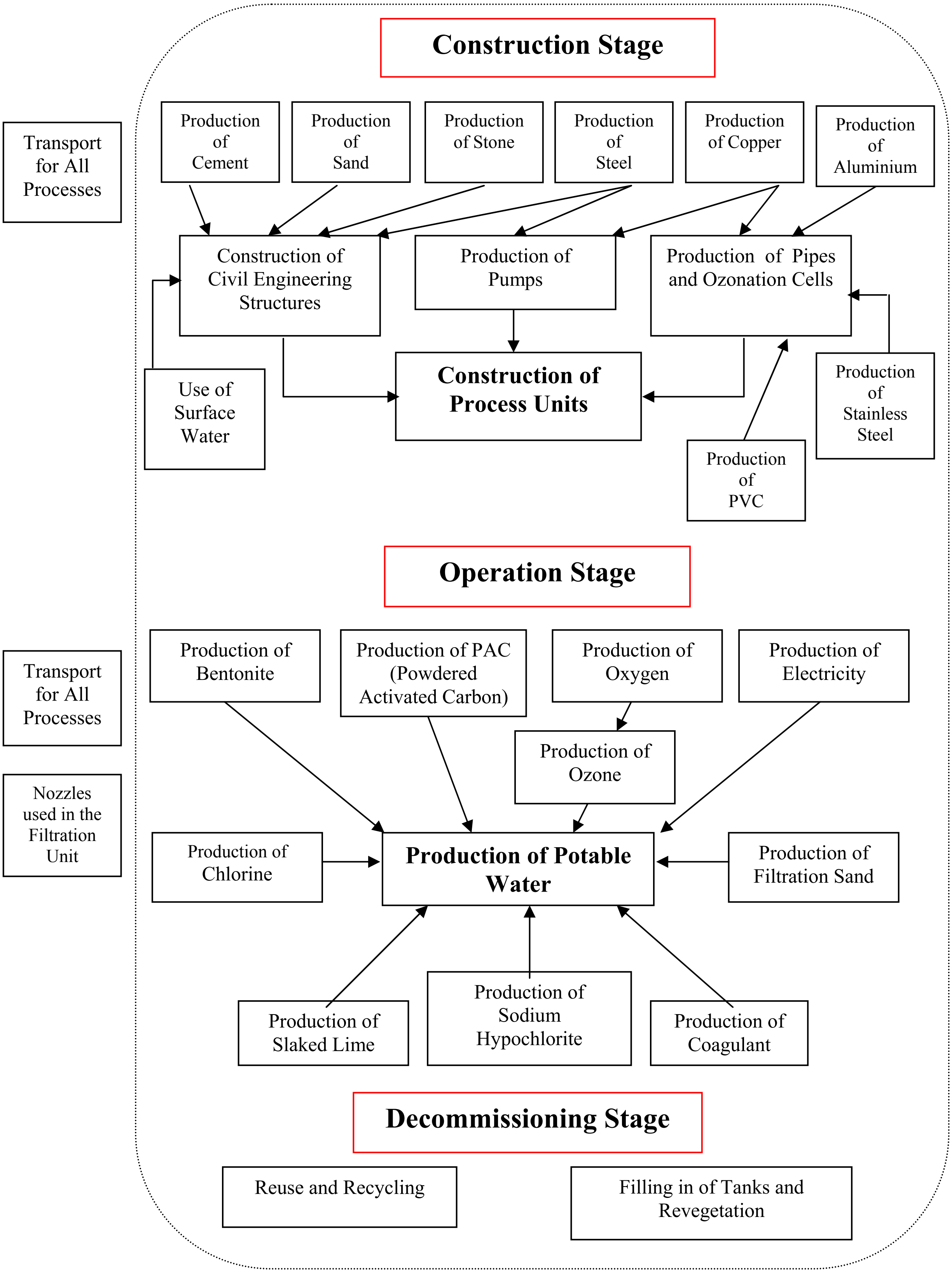


Figure 4.1: ***Life Stages and Processes Involved in the Production of Potable Water (Conventional Technology).***
The box represents the boundaries of the study, processes left out have not been included in the calculations.

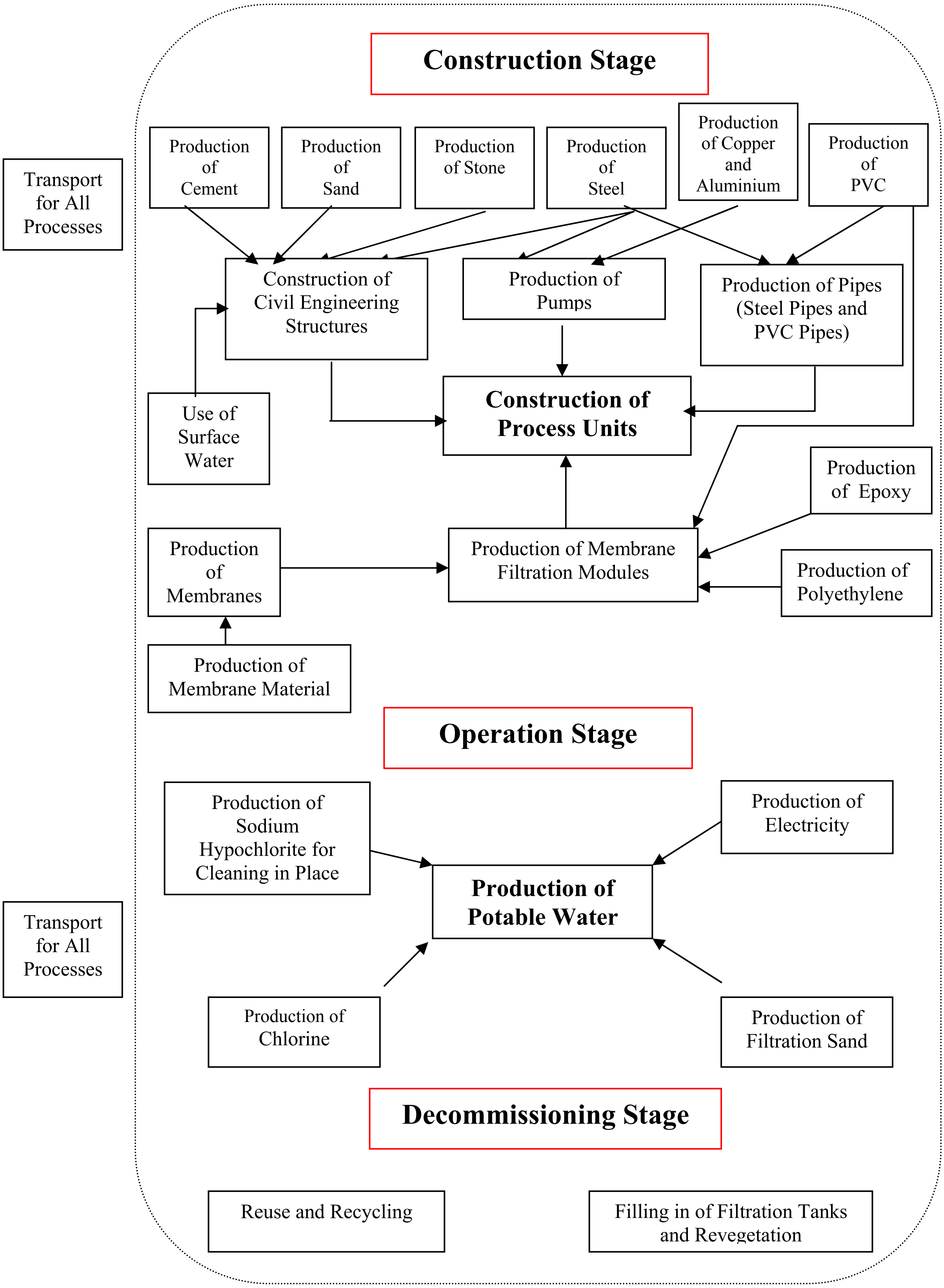


Figure 4.2: Life Stages and Processes Involved in the Production of Potable Water (Membrane Technology).

The box represents the boundaries of the study, processes left out have not been included in the calculations.

these processes and the environmental burdens have been attributed in totality to the main product. The Author is aware that this may add an additional burden to the studied system. However, most of the allocation was needed at the secondary and tertiary level of data collection, where material amounts per kilolitre of potable water get smaller and smaller, and therefore, this additional burden is considered to be small.

Data requirements and priority were established.

- Direct measurements and first hand data on the processes involved were preferable.
- Mass and energy balances were employed where no direct measurements exist, but enough data must be obtained for the processes under scrutiny.
- Calculations based on the technical literature were used only if direct data could not be obtained. If such calculations were used, the results were checked against international data on the same process or the same technology.
- Data collected for the operation stage of the two technologies of producing potable water covered a period of 28 months from 01 March 1998 to 30 July 2000. These data included monthly consumption of chemicals and electricity. The general timeframe for the data collected on other processes was proposed to be up to 10 years, however, data based on older technology had to be accepted for a few of the processes involved.
- The geographical area for data collection was South Africa. In cases where information was lacking and could not be obtained, European or global data had to be used.
- With regard to the nature of the technology involved, if no information was available an average of the actual technology (as opposed to best available technology or worst operating unit) was used.
- Data quality indicators are needed in order to conform to the ISO 14041 standard. The methodology for data quality is still under debate; therefore, one of the most accepted models - the data pedigree developed by Weidema (see Friedrich (2001) Appendix 7) – is used. The following indicators are considered: data precision, data completeness, data representativeness, data consistency and reproducibility.

A series of ***assumptions*** had to be made for both water treatment technologies. The main assumptions for the conventional technology are related to what is planned for the decommissioning stage, and to the calculations of the inputs for the polymeric coagulant. In the case of these calculations, it was assumed that for the production of allyl chloride and dimethylamine (the chemicals used for producing the monomer) the processes and the yields documented in the literature were appropriate to the actual manufacture. For the inputs on which international data had to be used, it is assumed that similar technology and processes as overseas are used in South Africa.

Another important assumption for the conventional technology was made with regard to the different life spans of the components of process units in a waterworks. It was assumed that civil engineering structures (tanks and buildings) have a life span of 30 years and that mechanical engineering structures (pumps and motors) have a life span of 10 years. The average life span for pipes was assumed to be 10 years, with the exception of steel, stainless steel and copper pipes which were assumed to last 30 years.

For the membrane plant a series of assumptions had to be made, not only with regard to individual processes on the plant, but also with regard to the entire design of the plant including the way it should be build, materials used, etc. These assumptions are enumerated in the following paragraphs.

- The membrane plant is housed in a warehouse type building with concrete foundations, steel structural frames and pillars and corrugated iron walls and roof. Calculations on the building materials needed for this type of structure were done with the help of Prof. King, School of Civil Engineering, University of Natal.
- The filtration unit preceding membrane filtration is the same in size and design as the one used for the conventional technology.
- In the membrane plant, the pressure needed in the different lines for the transport of water and for actual filtration is as follows: filtration pressure 1.5 Bar, pressure loss 0.4 Bar, backflush pressure 2.2 Bar and permeate pressure 1 Bar. These pressures are important, since they are the basis for pumping requirements and electricity consumption.
- The arrangement of the pipes in the membrane plant was considered modular in accordance with current practice. Calculations have been done for different scenarios including different numbers of modules per bank (see **Section 3.2.3** and **5.2**). At this stage a series of assumption had to be made with regard to pipe lengths and thickness. These assumptions are based on chemical engineering design principles and are presented in **Section 3.2.3**. Similar engineering design calculations were used for pumps. For pumps, in addition to the pressure and the flow needed, efficiency calculations were included in order to approximate electricity consumption (Friedrich (2001) Appendix 6).
- In the manufacture of the filtration membranes three chemicals (polysulphone, polyvinyl-pyrrolidone and poly(ethylene glycol)) are used on which no data could be obtained (see **Section 4.2.2**), therefore calculations had to be employed. It was assumed that processes and yields as presented in the literature are used in the actual production of these chemicals.
- In the case of overseas data, it is assumed that a similar technology is employed to produce the same substance in South Africa.

Limitations to this study were expected in certain general areas and a series of limitations specific to South Africa have emerged during the study. The specific limitations and problems experienced in this study are summerised below and more detail with regard to limitations of data obtained for individual processes is presented in the following section.

- The quality of the data obtained from some South African companies (e.g. Eskom and Polifin) was low and, therefore, South African data could not be used in a few instances.
- Some companies refused to release production data. As a result international data had to be used.
- Some data was not available locally and the producers overseas did not co-operate. Calculations base on literature had to be employed in these cases.
- In these calculations, energy requirements are usually underestimated, due to the non-existence of energy consumption data.
- Data quality assessment is incomplete for two processes, since a combination of actual data and calculations had to be used. The two processes are the production of the polymeric coagulant for the conventional technology and the production of membranes (i.e. three of the four chemicals used in the process) for the membrane technology.
- Validation of some data was impossible, since access to company records was not granted.
- The lack of valuation methods for South Africa and the methodological uncertainties associated with this step prevented the Author from performing this optional step.

With regard to a ***critical review*** process, this study will undergo two reviews. The first is through the Water Research Commission steering committee procedure and the second one through the examining process (internal and external) of the current thesis. The steering committee has a critical review function; however, in terms of the ISO 14040 standards it may be considered as an internal review process, since it has been involved with the project from the beginning and had the opportunity to influence the research. Publication according to ISO 14040 standards is not possible without an external review process. The external and the internal examiners may perform the external review process, since they are independent and have not influenced the study in any way.

Reporting is done in the form of a thesis and this final report to the Water Research Commission.

4.2 Collection of Data and the Inventory Analysis

The inventory analysis is the second phase of an LCA study and it involves data collection and calculation procedures to quantify relevant inputs and outputs of the system studied. The collection of data was the most difficult and time-consuming stage in the project. Once the processes involved in the production of potable water were investigated for both technologies, all the inputs to and outputs from each process were identified. Data were collected for all the processes used to produce these inputs (including energy) and for all processes used to deal with the outputs.

4.2.1 Collection of Data for the Conventional Technology

For the conventional technology, data collection started with the processes employed at Wiggins Waterworks and **Fig. 4.1** presents them in the context of the life cycle of the Wiggins Waterworks. In this figure the boundaries used for this study are illustrated and initially some of the processes now omitted, were included.

The collection of data for the conventional potable water case proved to be one of the most time consuming steps. Most of the chemicals involved in the treatment of water were not included in the database purchased, nor were they in three other commercial databases consulted, since they are considered to be specialty chemicals. Therefore, basic data on the processes involved were initially obtained from the literature and then from different companies. Actual production data were requested from the suppliers and producers. This proved to be a challenging task because many of the companies involved, especially the small and medium enterprises and companies with perceived environmental problems, were not prepared to release this data.

An important educational effort was needed to change the attitudes of the people involved. Several meetings and many phone calls were necessary until they were convinced that LCA is not a threat to their products or markets but can be quite the opposite. With one exception, the supplier of bentonite, it was possible to gather local data for the production processes of the chemicals involved in the conventional technology (calcium hypochlorite, molecular chlorine, sodium hypochlorite, polymeric coagulant, slaked lime and molecular oxygen). The situation was more complex with the polymeric coagulant, because many of the substances used in the blend are imported from overseas and Solvay (Belgium) and DuPont (Canada) had to be contacted for manufacturing data. However, there is very little control over the quality of the production data obtained, since the figures given by companies can not be directly checked. Where available, international figures were used to check if the range of the data given was correct. Data sheets containing information on the production process of each of the substances involved (excluding bentonite and the polymeric coagulant) are included in Friedrich (2001) (see Appendix 7).

In addition to data problems with external suppliers there were problems experienced with obtaining data from Wiggins Waterworks. Delays were experienced in collecting data on electricity consumption and on motors and pumps. Partially these delays can be explained by the preoccupation of technical staff with Y2K problems in October, November and December 1999 and partially by the nonexistence of data required. For example, there was no complete inventory of motors and pumps, and electricity consumption of individual processes is not measured. Special arrangements had to be made in order to obtain this data.

4.2.1.1 Obtaining Data for the Construction Phase

The main inputs in the construction phase were: cement, sand, stones and steel for reinforcement (see **Fig. 4.1**). Data on the production of cement were obtained from Natal Portland Cement. This company had a proactive attitude and allowed data collection and verification; therefore the quality of the data is good. The results, as presented in the final report presented to the company, are shown in Friedrich (2001) (Appendix 7). Some data on the production of construction stone and sand had to be estimated. For example, measurement data on emission gases resulting from the blasting explosions are not available. Locally, some studies have been done on underground explosions and estimates for blasting emissions have been obtained for underground conditions.

From the processes used in the construction phase, data collection problems have been experienced with regard to the production of steel and stainless steel, the production of copper and the production of PVC. Iscor Ltd. manufactures the iron from which steel and stainless steel is produced in South Africa and the company refused to release any data. It was motivated that the company is in the process of collecting this data to be aggregated in an international study initiated by the International Steel Manufacturer Association and at this stage their data set is incomplete and the results will be published by the association. PVC manufacturers approached motivated that they do not measure data such as air and water emissions. Therefore, international data had to be used for these processes. It became obvious in the assessment stage, that the construction stage is of secondary importance in the life cycle, since it accounts far less than 10 % of the environmental burden for most of the impact categories considered in the production of potable water. Therefore, further detailed time consuming investigations have not been carried out.

4.2.1.2 Obtaining Data for the Production Phase

In the production stage, the main inputs are electricity and the chemicals used (see **Fig. 4.1**). These chemicals are calcium hypochlorite, molecular chlorine, sodium hypochlorite, polymeric coagulant, slaked lime, activated carbon and molecular oxygen. Complete information on individual production processes has been obtained with four exceptions: bentonite, electricity, chlorine and the polymeric coagulant. Data on bentonite had to be obtained from international sources (Denmark, Germany) since the South African company involved did not forward the relevant information, even after several attempts and months of waiting. Data for the production of electricity has been obtained from Eskom; however, since electricity proved to be very important in the assessment phase, similar data on electricity production were used from a German coal plant. This was necessary because the data released by Eskom lacked detailed information, such as the trace elements emitted when burning coal and the complete list of inputs in the production of electricity. For the production of chlorine the same situation occurred. South African data on chlorine production was obtained from Polifin Ltd., however, detailed measurements on the inputs and outputs were not available and average international data had to be used. As mentioned in the previous section, the polymeric coagulant used is a blend of a variety of chemicals, most of them being imported and as a result South African data were not available. Solvay (Europe) and DuPont (Canada) were contacted, however, there were no LCA data available from these companies. Therefore, calculated data has been used. These calculations have been confirmed by Prof. Michael Overcash, Department of Chemical Engineering, North Carolina State University, USA. Prof. Overcash and his research group are doing extensive calculations for gate-to-gate life cycles on different chemicals based on chemical engineering process design (Overcash et al., 2000).

4.2.1.3 Obtaining Data for the Decommissioning Phase

Data for the decommissioning phase was obtained from the existing information on decommissioning of waterworks by Umgeni Water. Particular attention was paid to what is recycled and what is disposed of and how. Since Umgeni Water has decommissioned no waterworks of this size, some assumptions had to be made. The two major assumptions were that all materials which can be recycled will be recycled and that if tanks can not be used for other purposes (for example fish farming) they will be filled in with soil and the area revegetated (Mr. Thompson, personal communication, 1999).

4.2.2 Collection of Data for the Membrane Case

The collection of data for the membrane case proceeded in the same fashion and presented similar problems as the conventional case. However, as it can be seen from **Fig. 4.2** in the production of water by the membrane technology, there are some identical processes (production of cement, sand, stone, steel, copper and PVC) to the conventional technology, so separate collection of data for these processes was not repeated. The collection of data started with the production of the membranes and the production of filtration modules. It continued with the collection of data on how potable water is produced at the membrane pilot plant. An upscaling exercise followed whereby a large-scale membrane filtration plant was designed to produce the same quantity of potable water at the same quality as the conventional plant at Wiggins Waterworks. This was necessary to enable comparison between the two technologies using an LCA method, where a functional unit of 1 kL of water of a stipulated quality and scale was used.

As can be seen from **Fig. 4.2** there are only three new processes in the membrane case as compared with the conventional case. These are the production of epoxy resin, the production of polyethylene and the production of membranes. South African data for the production of epoxy resins and polyethylene was incomplete and therefore European data (contained in the GaBi 3 database) had to be used. The chemicals involved in the manufacture of membranes are: polysulphone, polyvinylpyrrolidone, poly(ethylene glycol) and N,N-dimethylformamide. Manufacturing data on the latter chemical was obtained form Prof. Overcash, University of North Carolina. Data on the production of membranes had to be calculated for three chemicals (polysulphone, polyvinylpyrrolidone, poly(ethylene glycol)) since the manufacturing company BASF Europe, was not prepared to co-operate. From the production data in the literature it was impossible to calculate complete energy figures, thus energy figures for these three chemicals may have been underestimated.

4.2.3 Validation of Data

Validation of data has been done for all of the processes presented in **Fig. 4.1** and in **Fig. 4.2**. For processes on which data was collected directly from the manufacturing company, validation was done by comparing this data with similar South African and/or international data. For example, data on cement production was compared with partial data (only greenhouse gases) from the South African Cement and Concrete Institute and with complete Danish data on the manufacture of a similar type of cement. For processes on which data could not be obtained or were incomplete, international data were used. The international data were obtained from the GaBi 3 LCA tool and for a few specialty chemicals (not included in the GaBi database) from Prof. Overcash University of

North Carolina. These data were validated overseas and therefore they were used as such. Calculated data was validated by checking initial assumptions and the calculations done.

4.2.4 Relating Data to Unit Processes and Functional Unit

The data for each process were scaled for the production of 1 kg of product when mass was used, for energy the unit required by GaBi 3 is the MJ. This involved simple conversion calculations. Data in this form were entered into the GaBi 3 LCA tool as new individual processes. A new flowsheet for each potable water producing technology (conventional and membrane) had to be drawn in this program. All the processes on each flowsheet were then scaled for the production of the functional unit (1 kL of potable water).

4.2.5 Data Aggregation and the Inventory

Data aggregation leads to the production of the inventory table (see **Fig. 2.1**), which is a collection of all normalised (or scaled) values for all inputs and outputs for all processes involved in a system. Two inventory tables have been produced, one for the conventional technology of producing potable water and one for the membrane technology. These inventory tables are presented in Friedrich (2001) (Appendix 8). To produce an inventory, the individual processes have to be entered with their inputs and outputs in the GaBi 3 tool, and the flowsheet has to be designed. The program then allows a system balance to be calculated and the inventory is automatically produced. Once the inventory is produced, the relative importance of the inputs and outputs from the different processes in relation to each other and the functional unit become evident. At this stage some of the processes may be excluded because of their small contribution and some additional processes may be required. By this the boundaries of the system under study are refined. However, for this study, for both systems (conventional and membrane) no process was excluded or included at this stage. The inventory table enables further calculations for the next phase of the LCA, namely the impact assessment.

4.3 The Impact Assessment and the Use of the GaBi 3 Life Cycle Assessment Tool

The impact assessment (**Fig. 2.1**) is the third phase of an LCA study. It has been defined as the phase of the LCA aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis (ISO 14040, 1997). In other words, it is the phase in which all the inputs and outputs from a system are related to potential environmental impacts and effects. These impacts and effects are quantified, allowing for comparison between two systems. For this phase the ISO 14042 standard (2000) stipulates three mandatory elements (category definition, classification and characterisation) and four optional elements (normalisation, valuation, grouping and data quality analysis) to be carried out. In this study the mandatory elements were believed to be sufficient and only these elements were performed on both systems (conventional and membrane). Sensitivity analyses, which are part of the optional data quality step, were also performed. The other optional steps were left out because they involve value choices and introduce a high degree of subjectivity without enhancing the value of the study.

The GaBi 3 LCA tool influences the way the three optional elements were performed. For the category definition step, this tool has a list of predefined categories and for the classification step the calculation tool of GaBi 3 is based on the CML (Center of Environmental Science, University of Leiden, The Netherlands) methodology. This is one of the most accepted and most used methodologies in Europe.

4.3.1 Category Definition

A number of environmental impact categories have been defined and used in LCA studies. These impact categories are selected in order to describe the environmental impacts caused by the system under study (see **Section 2.4.3**) and most of the current studies will select from the categories already developed. It is important that the impact categories selected are consistent with the goal and scope of the study (Jensen et al., 1997).

Categories developed so far in the literature have been grouped into two major classes:

- impacts due to depletion of resources (renewable and nonrenewable or sometimes biotic, abiotic and land use) and
- impacts due to pollution (greenhouse effect, depletion of the ozone layer, photochemical oxidant formation, acidification, eutrophication, terrestrial and aquatic ecotoxicity, human toxicity, working environment or occupational health, radiation, waste heat, noise and odour).

These impacts cause direct or indirect environmental degradation and sometimes human casualties.

In this study the impact categories predefined by the GaBi 3 tool were used. These categories are resource consumption (biotic and abiotic expressed together), energy consumption, global warming, ozone depletion, acidification, eutrophication (or nutrification), photochemical oxidant formation, radioactivity, aquatic ecotoxicity, terrestrial ecotoxicity and human toxicity. In addition to these categories, two separate ones considered important to the South African environment are discussed. These are water consumption and salination. These categories and some background information on their characterisation models, as described by the CML methodology, will be presented in the following paragraphs.

4.3.1.1 Global Warming

Global warming is the impact caused by the emission of certain substances (e.g. carbon dioxide) which absorb infrared radiation emitted by the earth, upsetting the earth's natural radiation balance. They cause an increase in the temperature of the atmosphere due to an additional greenhouse effect. Global warming is predicted to have far-reaching consequences such as rises of the sea level (due to the melting of icecaps and glaciers, as well as due to heat expansion of the oceans), regional climatic changes and other indirect negative impacts on ecosystems and society (spreading deserts, floods, loss of arable land and loss of habitats and species). The most important man-made greenhouse gases are carbon dioxide, methane, nitrous oxide and halocarbons (Hauschild and Wenzel, 1998).

Global warming characterisation factors have been developed through the work of the Intergovernmental Panel on Climatic Change (IPCC). This is an international panel of researchers established by the United Nations Environmental Programme (UNEP) and the World Meteorological Organisation (WMO). The reference substance is carbon dioxide and through modelling, characterisation (or equivalency) factors were developed for a number of greenhouse gases (Hauschild and Wenzel, 1998). The characterisation factors are sometimes called global warming potentials (GWP) and are expressed as kg carbon dioxide equivalents per kg of gas. A list of the characterisation factors for global warming is presented in Friedrich (2001) (Appendix 10) and it includes different time horizons (20, 100 and 500 years) for degradation. These are the values used by GaBi 3 in this study and a global warming potential can be calculated for all three time frames. For this research the 100 years timeframe was used since it is the one most frequently quoted by studies in the literature.

4.3.1.2 Stratospheric Ozone Depletion

The thinning of the ozone layer in the stratosphere is allowing increased levels of ultraviolet radiation to reach the earth, leading to impacts on humans (skin cancer and cataracts) and on ecosystems (plants and animals – e.g. effects on the phytoplankton around the South Pole) (Jensen et al., 1997). The concentration of ozone in this part of the atmosphere is a result of natural processes which break down and regenerate ozone. These processes are based on complicated reaction systems, including both solid phase and gaseous phase reactions, and a limited number of substances are involved (Hauschild and Wenzel, 1998). Most notably methane, nitrous oxide, water vapour, chlorine and bromine compounds (like methyl chloride and methyl bromide) are responsible for the breakdown of ozone molecules.

Human activities have increased the amount of substances involved in the breakdown of ozone and especially stable, long-lived chlorine and bromine containing hydrocarbons (i.e. chlorofluorocarbons or CFCs, tetrachloromethane, trichloroethane, etc.) are believed to contribute considerably. As a result a seasonal reduction of up to 50% of the ozone quantity above the South Pole has been observed since 1985. Less dramatic seasonal reductions (shorter and with less ozone depletion) were observed also over the northern hemisphere. As a result an international initiative called the Global Ozone Research and Monitoring Project was launched by UNEP (United Nations Environmental Programme) in co-operation with WMO (World Meteorological Organisation), NASA (National Aeronautics and Space Administration, USA), NOAA (National Oceanic and Atmospheric Admistration, USA) and the UKDoE (United Kingdom Department of Environment). This initiative developed models on ozone depletion mechanisms and calculated consecutive characterisation (or equivalency) factors for the major substances involved in ozone depletion (Hauschild and Wenzel, 1998). The reference substance for calculating characterisation factors is trichlorofluoromethane - CFC-11 (with the chemical formula $CFCl_3$). Friedrich (2001) (Appendix 11) presents a list of characterisation (equivalency) factors for ozone depletion and these are the ones used in the GaBi tool in this study.

4.3.1.3 Acidification

Acidification is the environmental impact caused by the build-up of protons in soils and lakes or, according to Hauschild and Wenzel (1998), it is a deterioration in the system's acid neutralisation capacity. Higher acidity in certain types of soils cause the mobilisation of different fixed ions, which are then absorbed by plants and damage them. Run-offs from acidic soils can harm aquatic ecosystems in the different lakes and rivers and in worst cases render them lifeless (Mannion and Bowlby, 1995). Acidification can be caused directly by acids and indirectly by acidic anhydrides (sulphur dioxide and trioxide and oxides of nitrogen) and ammonia. For the indirect mechanism, acidic anhydrides form the relevant acid after the contact with water (e.g. moisture in the atmosphere and in the soil). In the case of ammonia, hydrogen ions are released upon bacterial mineralisation.

The reference substance in the calculation of characterisation factors (or equivalency factors – EF) is sulphur dioxide and these factors are calculated based on the maximum quantity of hydrogen ions which can be released into the environment by an acidifying substance (Hauschild and Wenzel, 1998). Friedrich (2001) (Appendix 12) presents a list with the equivalency factors used in this study.

4.3.1.4 Eutrophication or Nutrification

Eutrophication or nutrification is an “overferilisation” of soils and waterbodies. In water it causes excessive algal growth and negative modification of the aquatic ecosystems involved (oxygen depletion and death of certain species). In soils it promotes monocultures and loss of biodiversity (Miller, 1995). Since nitrogen and phosphorous are the limiting nutrients for most of the aquatic systems, leaching of these nutrients into waterbodies results in eutrophication.

The calculation of characterisation (or equivalency) factors takes into account the amounts of phosphorous and nitrogen a substance can release into the environment when degraded and the reference substance used by GaBi 3 is phosphate. The equivalency factors for this category are listed in Friedrich (2001) (Appendix 13).

4.3.1.5 Photochemical Oxidant Formation

This environmental impact is caused by the presence of nitrogen oxides and volatile hydrocarbons in air in combination with sunlight. This combination results in the photochemical oxidation of hydrocarbons and the formation of smog. Smog is harmful to people, flora and fauna. Different photo-oxidants (some more stable than others) are the constituents of smog, the most important ones being ozone and peroxyacetyl nitrate (PAN) (Hauschild and Wenzel, 1998). The so-called winter smog occurs during cold conditions and is made up mainly by small particulate matter and sulphur dioxide. It causes respiratory problems (Miller, 1995).

The capacity to contribute to photochemical oxidant formation varies greatly between the different volatile organic compounds (VOC) and in the literature it is described by the Photochemical Ozone Creation Potential (POCP) (see Hauschild and Wenzel, 1998, for a detailed discussion of POCPs) for individual substances. The reference substance for photochemical oxidant formation is ethene (C_2H_4). The equivalency (or characterisation) factors are calculate by using POCPs and the list of characterisation factors used for this impact category in this study is presented in Friedrich (2001) (Appendix 14).

For the four impact categories presented above there is a high degree of agreement within the LCA community about the mechanisms of causality and the characterisation (or equivalence) factors derived. However, for the following impact categories associated with toxicity there is no consensus, and different methods of quantifying toxicity are used in the literature. Debate on methodology to quantifying toxicity (especially ecotoxicity) is expected to continue, because of the complexity of the mechanisms involved where emissions, fate, exposure, bioaccumulation and biodegradation have to be considered.

4.3.1.6 Aquatic and Terrestrial Ecotoxicity and Human Toxicity

Toxicity to humans, flora and fauna is caused by a variety of substances, ranging from carcinogens to persistent toxins such as heavy metals. Some act directly by poisoning organisms, others are more insidious, causing indirect harm to ecosystems.

In the GaBi 3 tool, the reference substance is 1, 4 dichlorobenzene (DCB). The characterisation (or equivalency) factors have been calculated based on the *Uniform System for the Evaluation of Substances* (USES), of the Leiden University (The Netherlands) and The Netherlands National Institute of Public Health and Environmental Protection. The model is described in detail in the publication *LCA Impact Assessment of Toxic Releases* (Publication No.1996/12 of the Dutch

Ministry of Housing, Spatial Planning and Environment Industry; Building, Manufacture and Consumers Directorate).

In calculating equivalency factors for toxicity, the following issues have been incorporated: lethal concentration for 50 % of a population (LC_{50}), no observed effect concentration (NOEC), equilibrium partitioning factors (soil – water, water – air and air – soil) and a bioaccumulation factor. However, it must be underlined again that biological processes involving toxicity are very complex and simplifications, as expressed by the equivalency factors, have to be regarded with caution. Some shortcomings of the methodology involved in the calculation of equivalency factors are:

- for some chemicals there are no experimental LC_{50} and NOEC values, approximations are used,
- the LC_{50} and NOEC values derived experimentally are determined by testing chemicals on one or sometimes up to three species, however, for other species these values are totally different,
- for heavy metals and pesticides background levels are important, however, in this method they are not considered.

There are international initiatives to reduce these shortcomings (most notably work done at the Universities of Leiden and Amsterdam – The Netherlands) and probably equivalency factors for ecotoxicity and human toxicity will be perfected in the future. The ones used in this study are presented in Friedrich (2001) (Appendix 15).

4.3.1.7 Resource and Energy Consumption

In this study, resource and energy consumption are taken into account with regard to total material consumption for a process and total energy consumption for a process. Since in this study the amounts of non-renewable substances per functional unit are small for both potable water producing technologies, these resources have not been treated separately and were included in the overall material consumption of the two technologies.

4.3.1.8 Water Consumption and Water Intensity of Processes

Water consumption should be included as an impact category because South Africa is a water scarce country. It is a semi-arid country with an average rainfall of ca. 500 mm p.a. This is well below the world average of 860 mm/year. There is also a problem with the geographical distribution of the water supplies in relation to the demand, in the sense that the demand is greatest in the interior of the country, whilst untapped water resources are situated along the coast (Middleton, 1998).

With planned industrial growth and increasing demand for water, every possible step should be taken towards the optimum use and recovery of water. The South African industry accounts for about 7% of the consumption of fresh water in South Africa, however, the volume and nature of wastewater generated in industry has a substantial effect on the quality of water in the country (Middleton, 1998).

The consumption of water expressed as litres of water per kilogram of product for each process was initially calculated. In a next step the water consumption for each of the technologies under study (conventional and membrane) was calculated as litre of water per functional unit (1 kL of potable water). It was thought that these consumption figures should give a measure of the water intensity of the processes considered. However, for many of the processes on which data from overseas were used, water consumption figures were lacking. As a result the calculated water consumption for each technology was incomplete and a comparison between technologies was not possible. This shortcoming highlights the need to develop a South African methodology to assess the importance of water consumption and the water intensity of industrial processes.

4.3.1.9 Salination

Salination is another impact category of particular importance in the South African environmental context. Salination is listed as one of the key pollution areas in this country (Department of Environmental Affairs and Tourism, 2000) and has important economical and financial implications (Urban Econ, 2000). Salination is defined as the increased concentration of dissolved inorganic compounds in waterbodies and it causes a decrease in the quality of water. The effects on the users are known and in most cases pre-treatment of water is necessary due to the decreased quality of water. However, little is known on the effects of salination on aquatic ecosystems.

There is no developed impact assessment methodology for salination and this problem has to be addressed urgently by initiating research on the topic. Of special interest are the chemical species which play an important role in this process, the development of equivalency factors and the choice of a reference substance. Salination was not used as a quantitative impact category in this study.

4.3.2 Classification

Classification is the second step in an LCA impact assessment. This is the step in which all the inputs and the outputs from an inventory list are assigned to the impact categories chosen (see **Section 2.3.3.3**). This step was done automatically by the GaBi 3 LCA tool used in this study. The database created for each inventory has a search field which enables this function. Therefore, it is important when entering data about processes to check that all inputs and outputs have this field correctly entered.

4.3.3 Characterisation

Characterisation is the third step in an impact assessment in an LCA study and it entails mathematical calculation procedures in order to obtain one score for each impact category (see **Section 2.4.3**). The characterisation (or equivalency) factors used for each category in this study are presented in Friedrich (2001) (see Appendices 10 to 15). The mathematical calculations, whereby the amount of a substance is multiplied by its equivalency factor and the adding of scores for each impact category, are done automatically by the GaBi 3 tool. Contributions of each substance group (like heavy metals to air) to the overall score of an impact category can be delimited by using the GaBi 3 tool, and the results can be displayed in the form of tables or in the form of graphs. The tables produced by the GaBi 3 tool are of limited use since they are highly aggregated, however, graphs are more explicit, as can be seen in **Chapter 5**.

The last stage in conducting an LCA according to ISO 14040 is the interpretation stage. In this report the interpretation stage is presented as two different chapters, since, from an academic point of view, it represents the results and discussion chapter and the conclusion and recommendation chapter.

CHAPTER 5
RESULTS AND DISCUSSIONS

Interpretation is the fourth phase in an LCA study and according to the ISO standards the objectives of this stage are to analyse results, explain limitations, reach conclusions and provide recommendations. For this research project the interpretation phase is presented in **Chapter 5** and **Chapter 6**. This chapter presents the environmental profiles of the two systems studied for the production of potable water. Individual contributions to each impact category will be discussed and the major contributors underlined. The comparison between the two different technologies is presented as well as a comparison of the results of this study with those of similar international studies.

5.1 Results for the Conventional Technology for Producing Potable Water

Individual processes associated with each of the three stages (construction, operation and decommissioning) are presented in **Fig. 4.1** and data were collected on these processes. With regard to the inputs, the first two impact categories considered are resource consumption and energy consumption and the values for these two categories are presented in **Table 5.1**. This table shows that the operation stage carries the highest burden with regard to material and energy consumption and the decommissioning stage the lowest.

Table 5.1. Material and energy consumption for the conventional technology

Stage	*Material Consumption (kg/kL)*	*Energy Consumption (MJ/kL)*
Construction	0.0515	0.0873
Operation	2.7000	2.0670
Decommissioning	0.0002	0.0015
Total	2.6515	2.1552

With regard to the outputs, by using the data gathered and the LCA methodology as presented in **Chapter 4**, the environmental profile for the conventional technology was calculated. This environmental profile is presented in **Table 5.2.**

Table 5.2. The overall environmental profile for the production of potable water by the conventional technology (worst case scenario)

Impact Category	*Score*	*Unit*
Global Warming Potential	1.85E-01	kg CO_2 equivalents
Ozone Depletion Potential	3.61E-09	kg CFC-11 equivalents
Acidification Potential	1.10E-03	kg SO_2 equivalents
Eutrophication Potential	7.40E-05	kg Phosphate equivalents
Photo-oxidant Formation Potential	1.57E-05	kg Ethene equivalents
Aquatic Ecotoxicity Potential	2.73E-03	kg DCB* equivalents
Terrestrial Ecotoxicity Potential	2.59E-01	kg DCB equivalents
Human Toxicity Potential	4.09E-03	kg DCB equivalents

**DCB is 1, 4 dichlorobenzene*

The overall 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 operation units. **Table 5.3** presents the scores for these stages and their proportion to the overall score. Note that the units for the impact categories are the same as in **Table 5.2** and are therefore not repeated.

Table 5.3: Environmental profiles for the construction, operation and decommissioning for the conventional technology (worst case scenario)

Impact Category	*Construction*	*Operation*	*Decommissioning*
Global Warming Potential	1.14E-02 (6.2)*	1.73E-01 (93.7)	1.48E-04 (0.1)
Ozone Depletion Potential	3.90E-10 (10.8)	3.21E-09 (88.9)	9.16E-12 (0.3)
Acidification Potential	7.81E-05 (7.1)	1.02E-03 (92.9)	4.92E-07 (0.0)
Eutrophication Potential	8.47E-06 (11.4)	6.55E-05 (88.5)	4.30E-08 (0.01)
Photo-oxidant Formation Potential	2.48E-06 (15.8)	1.32E-05 (83.9)	5.67E-08 (0.4)
Aquatic Ecotoxicity Potential	6.25E-05 (2.3)	2.66E-03 (97.7)	1.52E-06 (0.1)
Terrestrial Ecotoxicity Potential	2.73E-02 (10.6)	2.31E-01 (89.2)	5.85E-04 (0.2)
Human Toxicity Potential	7.39E-04 (18.1)	3.31E-03 (81.0)	3.75E-05 (0.9)

** the values in brackets represent the percentage value of the total score for that category*

From the percentage values presented in brackets, one learns that for the conventional technology the operation stage (the stage in which potable water is produced) has the most significant contribution for the overall environmental profile. For all of the categories considered the contribution from this stage is greater than 80%, with some of the categories such as aquatic toxicity, global warming and acidification being greater than 90%. Since this stage is predominant, the major contributors to the environmental scores for each impact category were deaggregated. The flow diagram used to model this stage in the GaBi 3 software tool is presented in **Fig. 5.1**.

All the processes presented in **Fig. 5.1** have been traced to the interface between the system (technoshpere) and the environment (biosphere), i.e. the inputs have been followed to raw materials extracted and the outputs have been classified as usable products and emissions to water, air and soil. The thickness of the arrows in the diagram is proportional to the quantity of mass transferred from one process to another (with the exception of electricity and steam where energy units (MJ) are used).

As can be seen in **Fig. 5.1**, some of the inputs (e.g. chlorine) are used directly in the production of water but also indirectly for the production of other chemicals which enter the production process. Note that in the case of aluminium production, data on the production of aluminium sheets was chosen to be closest to those of aluminium chips which are used in the production process for aluminium chloride hydrate. The abbreviation in the process boxes identify the origin of the data used (i.e. EU stands for European Union, APME for Association of Plastic Manufacturers in Europe, etc., see the list of abbreviations).

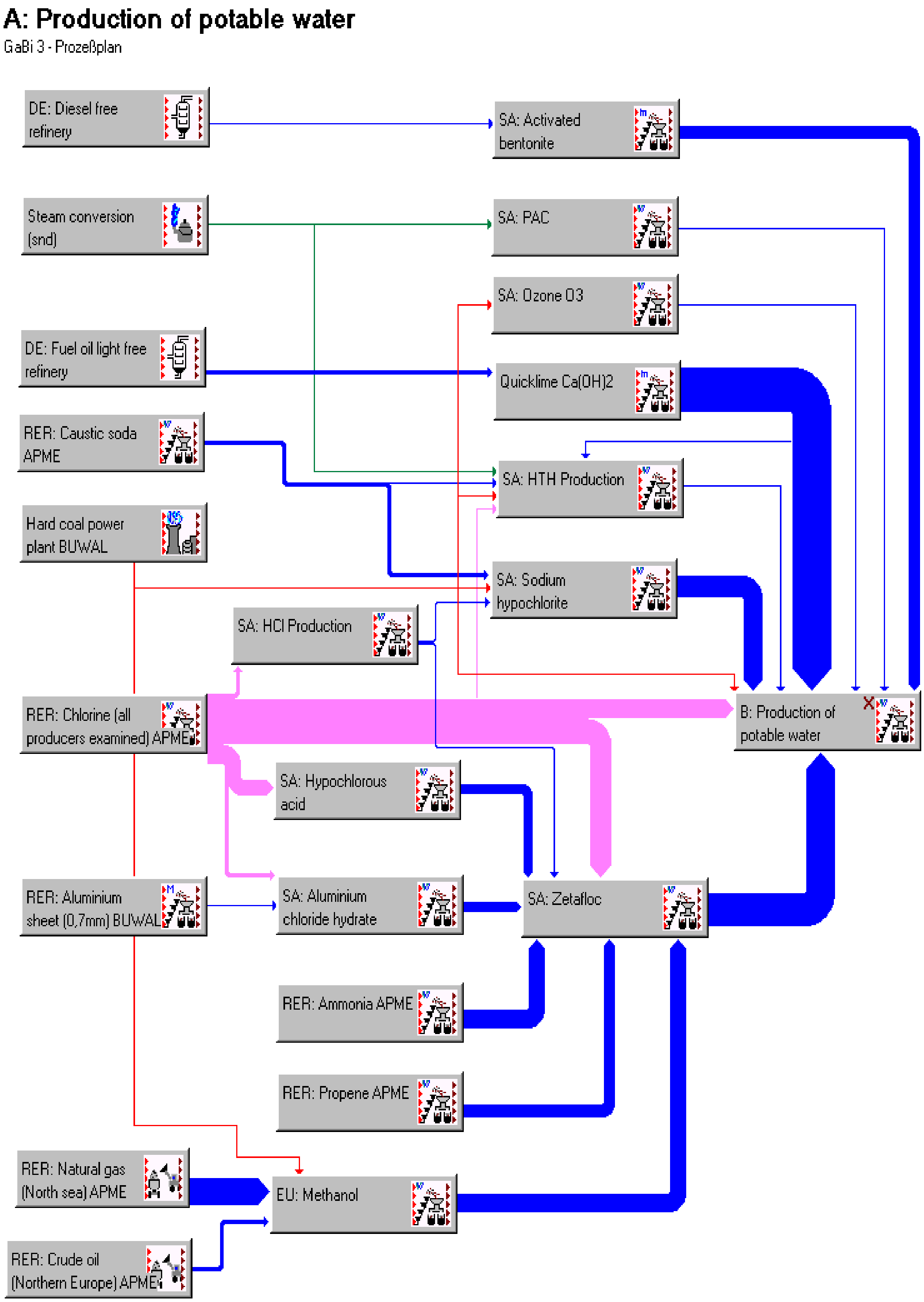


Figure 5.1: ***GaBi 3 Process plan for the conventional technology for the production of potable water – operation stage***

For the impact category of ***global warming*** the major contribution in the operation stage is traced back to the production of electricity from hard coal. Electricity production accounts for about 93% of all the contributions to global warming from the operation stage and, as shown in **Fig. 5.2**, the inorganic emissions into air resulting from this process are the main contributors. The chemicals with the highest contributions are carbon dioxide and methane. For the operation stage, carbon dioxide accounts for about 85% of the score and methane for about 8%.

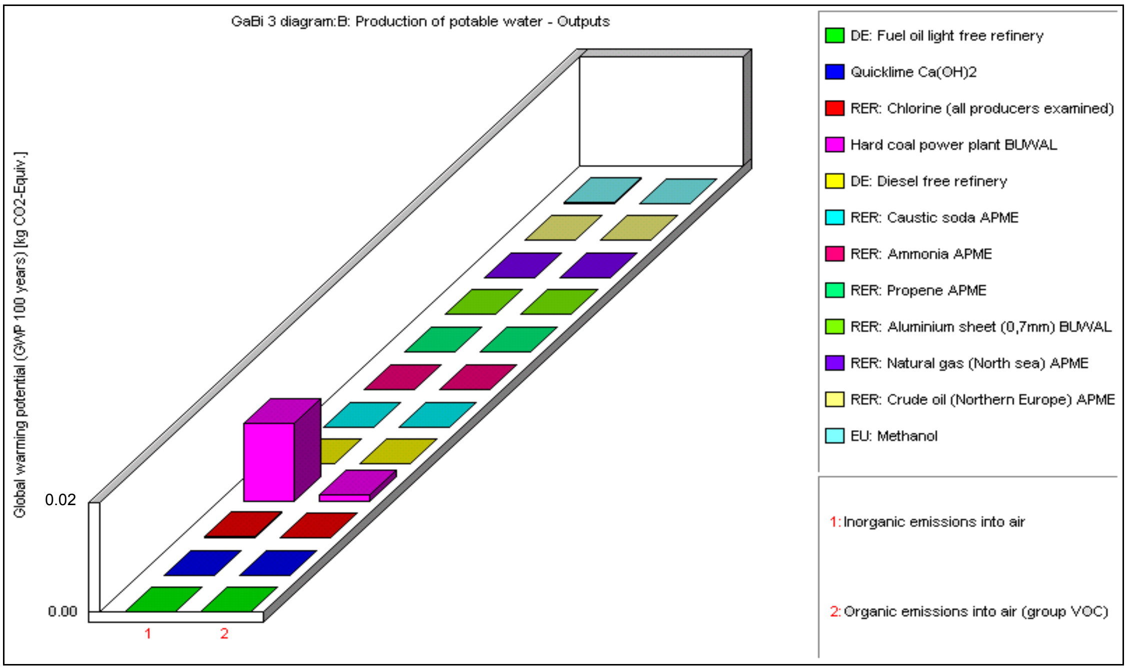


Figure 5.2: Contributors to global warming for the operation stage (conventional technology)

For the construction stage (which accounts for about 6% of the overall, see **Table 5.2**) the two main contributing processes are the production of steel, accounting for aprox. half (of the 6.2% overall), and the production of cement, which accounts roughly for the other half (49.3%) (of the 6.2% overall). For the decommissioning stage the main contribution to global warming (96% of the 0.1% overall) comes from the recycling of steel from pipes and pumps.

The recycling of steel has an environmental burden, however for this system the burden is small. It must be noted that besides this burden, steel recycling has positive environmental consequences because it replaces a virgin non-renewable resource. In this study, this positive spin-off is taken into account only with regard to the mass flow (i.e. the amount of virgin steel which does not have to be produced) and not with regard to emissions (i.e. the emissions which are not produced due to the replacement of virgin steel with recycled steel). Therefore, the environmental burdens are not completely compensated for by the benefits. In this case, because of the small amounts involved, this shortcoming is considered to be of minor importance. However, in other studies it may be important, and this aspect should not be neglected.

For the impact category of ***ozone depletion*** the same pattern is observed, with electricity generation being the main contributor. For the operation stage 95% (of the 88.9% overall, see **Table 5.2**) come from VOC (volatile organic compounds) emissions due to the generation of electricity from coal. The remaining 5% of the overall are traced to the production of aluminium. For the construction stage (which accounts for 10.8% of the overall) the two contributing processes are steel production (95% of the 10.8% overall) and aluminium production (the rest).

For the decommissioning stage the recycling of steel has the highest contribution (92% of the overall 0.25%).

For the impact category of ***acidification***, of the 92.8% (see **Table 5.3**) contribution due to the operation stage about 84% are attributed to the generation of electricity, specifically to the inorganic emissions to air. **Fig. 5.3** illustrates these contributions. When deaggregating further it becomes evident that sulphur dioxide and nitrogen oxides are the dominant inorganic contributors. About 59% of the acidification potential of the operation stage are attributed to sulphur dioxide and about 26% to nitrogen oxides due to the generation of electricity.

In the construction stage, the main contributor to acidification comes from the production of cement (76.6% of the overall 7.1%).

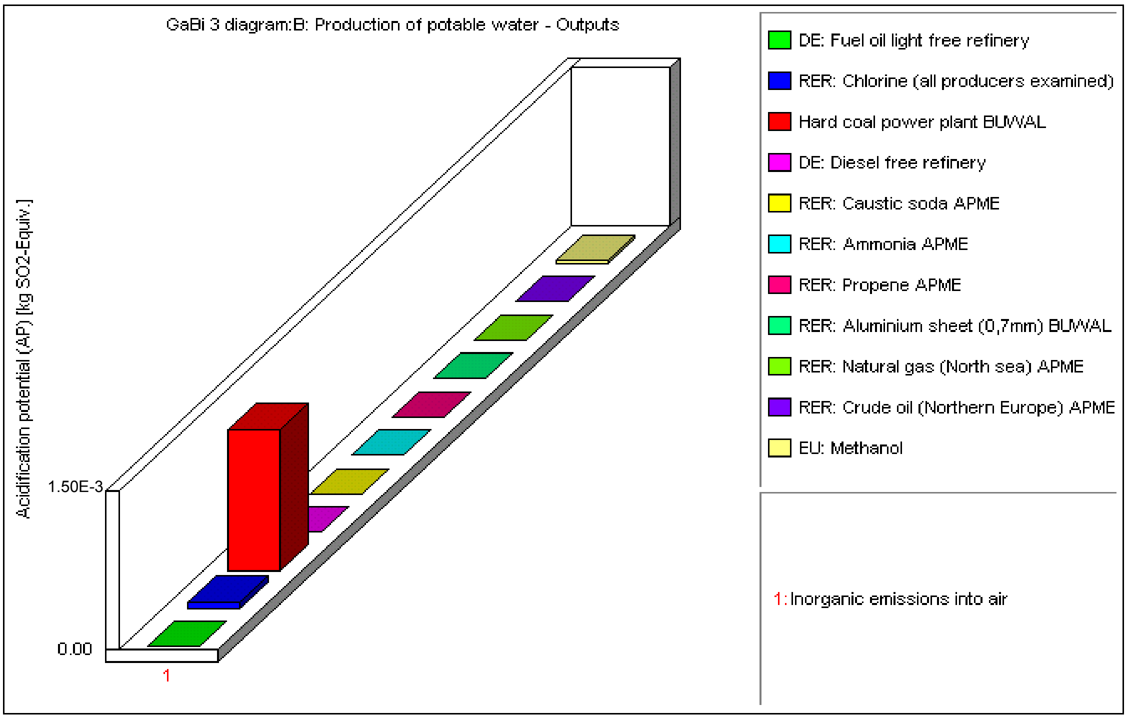


Figure 5.3: Contributors to acidification for the operation stage (conventional technology)

A similar pattern of contributions is observed with regard to ***eutrophication*** (or nutrification). In the operation stage 92% of the 88.5% overall (see **Table 5.2**) is traced to the generation of electricity in hard coal power plants as shown in **Fig. 5.4**. In the construction stage the production of cement has the highest contribution (83% of the overall 15.8 %) and in the decommissioning stage the recycling of steel contributes the most (92% of the overall 0.1%).

For the dominating stage (i.e. the operation stage) the main contributors to this impact category are the inorganic emissions to air (responsible for about 84% of the overall 88.5%) and inorganic emissions to water. Nitrogen oxides to air account for about 75% of the 88.5% overall and phosphates emissions to water account for about 13% of the overall. These emissions are both traced back to the generation of electricity.

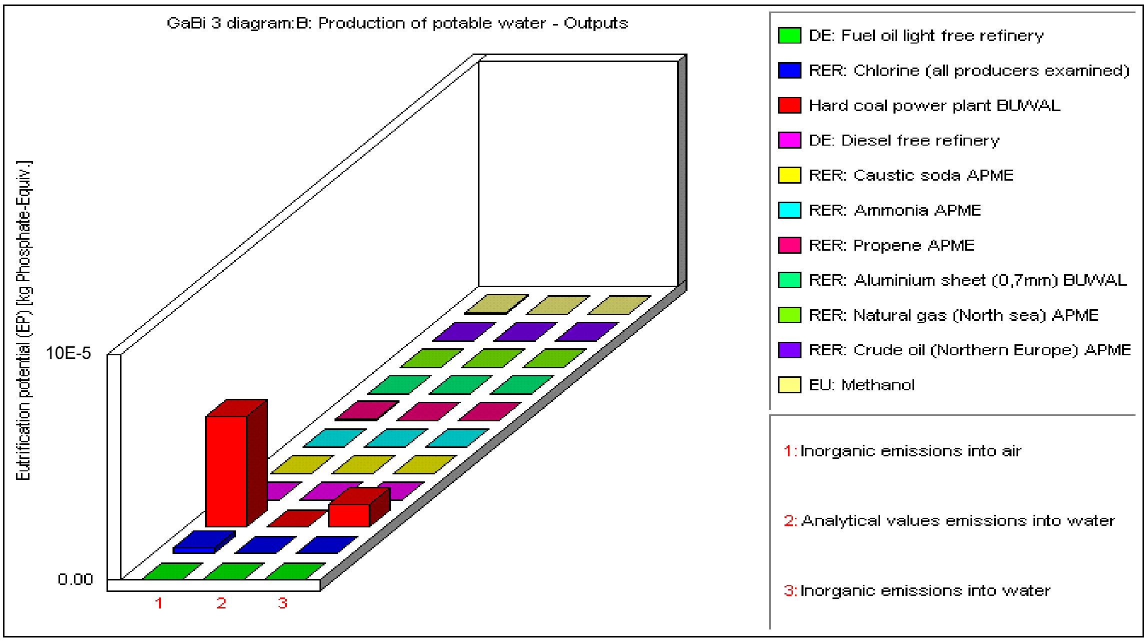


Figure 5.4: Contributors to eutrophication for the operation stage (conventional technology)

For the environmental impact category of ***photo-oxidant formation*** (or smog formation) the main contributor in the operation stage (which accounts for 83.9% of the overall) is the generation of electricity (responsible for 87% of the 83.9% overall). For the construction stage 90% of the 15.8 % overall is traced to steel production and for the decommissioning stage 90% of the 0.4% overall is traced to steel recycling.

For the three ***toxicity*** impact categories (terrestrial, aquatic and human) the major contributors and in the different stages are presented in **Table 5.4**.

From **Table 5.4** it can be observed that in each of the life stages of the waterworks the same processes dominate these three toxicity categories. In the construction stage the dominant process is steel production, in the operation stage it is electricity generation in hard coal power plants and in the decommissioning stage it is the recycling of steel. For these three toxicity categories, terrestrial toxicity (notably in the operation stage) has the highest absolute value.

Table 5.4: Scores and contributions for toxicity (conventional technology)

Toxicity	***Contribution and Dominant Process***		
	Construction	***Operation***	***Decommissioning***
Aquatic	6.25E-05* (2.3)** of which 99% from steel production	2.66E-03 (97.7) of which 97% from electricity generation	1.52E-06 (0.1) of which 96% from recycling of steel
Terrestrial	2.73E-02 (10.6) of which 99 % from steel production	2.31E-01 (89.2) of which 94% from electricity generation	5.85E-04 (0.2) of which 98 % from recycling of steel
Human	7.39E-04 (18.1) of which 98% from steel production	3.31E-03 (81.0) of which 97% from electricity generation	3.75E-05 (0.9) of which 100% from recycling of steel

** the units for all toxicity values are kg DCB (1, 4 dichlorobenzene) equivalents.*
*** the values in brackets represent the percentage contribution from the total score for that category*

For all three toxicity categories the main contributors are heavy metals. In the operation stage (which dominates all three categories) aquatic ecotoxicity is due to nickel emissions to water (accounts for about 75% of the 97.7% overall). For the same stage terrestrial ecotoxicity is due to cadmium (40% of the overall), mercury (33%), zinc (15%) and nickel (8%) to air. For human toxicity the main contributors are lead emissions to air (56% of the overall for the operation stage) and nickel to air (21% of the overall for the operation stage). All these heavy metals are traced back to the generation of electricity from coal.

5.2 Interpretation of the Results for the Conventional Technology

From the scores presented in the above section it becomes evident that electricity generation is the dominant overall process for all impact categories considered. Therefore, it is important to examine how electricity is consumed in the system and to identify processes which have the highest consumption. However, electricity consumption has to be considered together with electricity generation and both processes are an integral part of the energy balance of the system. **Table 5.5** presents an overview of the energy values of the system investigated in the production of potable water by the conventional technology.

Two types of situations have to be distinguished and clearly delimited. In the first situation electricity generation is presented as a separate process, which is subsequently linked to the processes which consume electricity (**Fig. 5.1**). In this section this is referred to as direct electricity. An example of a process which needs direct electricity is the production of sodium hypochlorite (**Fig. 5.1**) In the second situation electricity consumption and generation are followed up to the interface system-environment and the inputs and outputs are included with the inputs and outputs of a particular process. Examples of processes in which electricity consumption and generation have been included are the production of ammonia, propene and chlorine. For these processes a link to the process of electricity generation would be double counting and a mistake in the inventory.

From this table it is obvious that the process with the highest energy consumption in the system is the generation of electricity. To produce the 0.544 MJ/kL direct electricity needed for the processes presented in **Fig. 5.1** 1.813 MJ/kL energy is needed. This represents an energy efficiency of 30 % (for generation and transmission), close to the value of 34 % achieved by Eskom in South Africa (Eskom Environmental Report, 1999).

Direct electricity is used in the system as follows: for the on-site production of potable water (excluding ozone production) 0.306 MJ/kL, for sodium hypochlorite production 0.233 MJ/kL, for ozone production 0.004 MJ/kL, for methanol production 0.001 MJ/kL and for HTH production 2.27E-05 MJ/kL (**Table 5.5**). From these consumption values at the waterworks, the electricity consumed on-site for the production of potable water and for the production of ozone totals 0.310 MJ/kL and it represents about 57% of the direct electricity demand. However, to produce this direct electricity about 1.033 MJ/kL are needed, which means that out of the 2.067 MJ/kL energy needed in the operation stage (**Table 5.1**), 50% is used at the waterworks and is under the control of water authorities. Therefore, it is useful to look at the electricity consumption of individual processes employed at Wiggins Waterworks.

Table 5.5. Energy values for the operation stage (conventional technology)

Process / Substance	***Energy Input – Calorific Value (MJ/kL)***	***Proportion %***
Direct electricity	0.544	N/A
Potable water production**	0.306	N/A
Sodium hypochlorite prod.**	0.233	N/A
Ozone production**	0.004	N/A
Methanol production**	0.019 (0.001 as direct electricity)	0.88
HTH production**	2.27E-05	N/A
Total energy in the system		
Direct electricity generation	1.813	87.72
Propene production	0.065	3.15
Chlorine production	0.059	2.86
Natural gas	0.053	2.57
Light oil - fuel	0.015	0.73
Crude oil	0.011	0.53
Aluminium production	0.009	0.45
Quicklime production	0.008	0.39
Ammonia production	0.008	0.39
Caustic soda production	0.006	0.29
PAC production	2.55E-04	0.02
Steam conversion	1.23E-04	0.00
Diesel – fuel	1.75 E-04	0.01
Total	**2.067**	**99.99**

*** The electricity consumed by these processes totals up to 0.544 MJ/kL direct electricity, which needs to be generated. To generate these 0.544 MJ/kL about 1.813 MJ/kL are needed. Out of the 0.019 MJ/kL energy inputs for the production of methanol 0.018 MJ/kL are added towards the total and only 0.001 MJ/kL are direct electricity.*

Table 5.6 presents the electricity consumption of individual processes used in the production of potable water at Wiggins Waterworks and Friedrich (2001) (Appendix 16) shows in detail how these values have been obtained.

From this table it can be seen that the process with the highest electricity consumption is ozonation (4341.4 kWh/d), a process which includes the production of ozone (1200 kWh/d) and the thermal destruction of ozone emissions (3141.4 kWh/d). The second highest electricity consumer is the sludge plant and the third highest the filtration unit. These processes should be a priority for energy efficiency measures in order to improve the total environmental performance of the Wiggins Waterworks. Since ozone destruction needs more energy than ozone production it is worth investigating other methods of destruction which should be less energy intensive.

The electricity values for the production of various chemicals used in the production of potable water could be manipulated indirectly by using chemicals which need less electricity for their production instead of chemicals which need more electricity. The overall reduction of the electricity used in the system will reduce the environmental burdens of the system and will result in an improved environmental performance as measured by the LCA.

Table 5.6: Electricity used by individual processes at Wiggins waterworks

Process	***Electricity Consumption (kWh/d)***	***Proportion %***
Sludge plant	2272.3	18.0
Filtration (Machine Hall)	1428.0	11.3
Clarifiers	1372.0	10.9
▪ pulsators	1108.0	8.8
▪ compressors	264.0	2.1
Chemical addition	823.6	6.5
PAC Plant	16.3	0.1
Ozonation:		
▪ thermal destruction	3141.4	24.9
▪ pre-ozonation thermal destruction unit	1610.9	12.8
▪ intermediate ozonation thermal destruction unit	1530.5	12.1
▪ ozonators	1200.0	9.5
Miscellaneous:		
▪ wash water recovery	1242.0	9.9
▪ mixers and pumps for homogenisation	660.0	5.2
▪ sample pumps	66.0	0.5
▪ res outlets	312.0	2.5
▪ pre-chlor sample pumps (post clarifiers)	26.4	0.2
▪ sodium hypo pump station	52.9	0.4
Total	**12612.9**	**99.9**

5.3 Results for the Membrane Technology for Producing Potable Water

The life cycle stages considered for potable water production by membrane technology are the same as for the conventional technology, namely the construction stage, the operation stage and the decommissioning stage. For this technology eight different scenarios were considered (as presented in **Section 3.2.2**) and are shown in **Table 5.7**.

Table 5.7. Scenarios for the membrane technology

Scenario	***Module Length (m)***	***Flux (L/m^2h)***	***Modules per bank***	***Modules needed***
1A	1.250	50	30	4 740
1B	1.250	50	60	4 740
2A	1.250	100	30	2 370
2B	1.250	100	60	2 370
3A	1.600	50	30	3 240
3B	1.600	50	60	3 240
4A	1.600	100	30	1 620
4B	1.600	100	60	1 620

Calculations were done for each of these scenarios with regard to inputs and outputs and also environmental profiles have been produced for all eight scenarios. For a better understanding of the presentation of the results, the scenarios are defined as shown in **Table 5.7**. Details on the technical specification of the membrane filtration modules are presented in Friedrich (2001) (Appendix 5).

The first part of this section presents the environmental scores for each of the impact categories considered. Since environmental scores are very similar for some of the eight scenarios, an average value may be presented together with the highest and the lowest contribution. The second part of this section will present an analysis of the environmental scores in relation to the different scenarios. Finally, the third part of this section will present an interpretation of the environmental scores in relation to the processes identified as having the highest environmental contribution.

5.3.1 Environmental Scores for the Membrane Case

As with the conventional technology, the first two parameters on the input side are material consumption and energy consumption. **Table 5.8** presents the material consumption and in **Table 5.9** the energy consumption for the eight scenarios considered is presented.

Table 5.8. Material consumption for the membrane technology

Scenarios	*Total*	*Stages*		
		Construction (kg/kL)	*Operation (kg/kL)*	*Decommissioning (kg/kL)*
1A	2.343	0.043	2.300	0.00054
1B	2.343	0.043	2.300	0.00052
2A	2.324	0.024	2.300	0.00030
2B	2.424	0.024	2.400	0.00030
3A	2.432	0.032	2.400	0.00041
3B	2.332	0.032	2.300	0.00038
4A	2.318	0.018	2.300	0.00032
4B	2.317	0.017	2.300	0.00023

Table 5.9. Energy consumption for the membrane technology

Scenarios	*Total*	*Stages*		
		Construction (MJ/kL)	*Operation (MJ/kL)*	*Decommissioning (MJ/kL)*
1A	2.033	0.068	1.960	0.00487
1B	1.999	0.067	1.926	0.00460
2A	1.966	0.038	1.925	0.00262
2B	2.464	0.038	2.422	0.00264
3A	2.649	0.055	2.590	0.00365
3B	2.086	0.054	2.028	0.00337
4A	2.061	0.031	2.027	0.00285
4B	1.836	0.027	1.806	0.00205

There are two important observations to be made from **Table 5.8** and **Table 5.9**. Firstly, for all membrane scenarios the operation stage carries the highest burdens with regard to the materials and the energy consumed to produce potable water. The decommissioning stage carries the smallest burdens. Secondly, from the eight scenarios considered, scenario 4B (long, high flux modules arranged in larger banks) requires the smallest amounts of materials and energy. Scenario 3A (long, low flux modules arranged in smaller banks) the highest. Therefore, from a material and energy point of view, the flux and the arrangement in banks are more important than the module length.

From **Tables 5.7** and **5.8** it can be seen that the scenarios needing the largest number of modules are the scenarios with the largest material consumption per volume of water produced. However, the arrangement of modules in the banks also plays a role, albeit a small one, since scenarios with the same number of modules may have slightly different specific material consumption values.

A summary of all eight environmental profiles is presented in **Table 5.10**. The scores are based on the outputs, in the form of emissions to air, water and soil, contributing to different environmental impacts. An environmental profile was calculated for all eight scenarios presented. The calculations were based on individual inventories produced for each of these scenarios. For a better overview, the environmental scores were normalised by dividing all the scores of an impact category by the smallest score (**Table 5.10**). This normalisation should not be confused with the LCA step with the same name, since the procedure is different.

From the eight scenarios for which environmental profiles have been produced, scenario 4B has the lowest scores for all the impact categories considered and scenario 3A the highest. For the outputs, as reflected in the different categories, the operation stage carries the highest scores for all the impact categories and for all the scenarios considered.

Table 5.10. Environmental profiles for the membrane technology scenarios

Impact Category	*Unit*	*Scenario*							
		1A	*1B*	*2A*	*2B*	*3A*	*3B*	*4A*	*4B*
Global Warming	kg CO2 Equiv.	0.22117	0.216541	0.214815	0.270032	0.289511	0.227059	0.225819	0.201038
Normalised Value*		1.10	1.08	1.07	1.34	1.44	1.13	1.12	1.00
% from Operation Stage		98.1	98.0	98.8	99.0	98.8	98.4	98.9	98.9
Ozone Depletion	kg CFC-11 Equiv.	7.63E-10	7.43E-10	7.12E-10	8.75E-10	9.55E-10	7.58E-10	7.40E-10	6.64E-10
Normalised Value		1.15	1.12	1.07	1.32	1.44	1.14	1.11	1.00
% from Operation Stage		83.2	83.9	87.6	89.9	88.2	86.7	88.8	87.9
Acidification	kg SO2 Equiv.	1.39E-03	1.36E-03	1.35E-03	1.70E-03	1.82E-03	1.43E-03	1.42E-03	1.26E-03
Normalised Value		1.09	1.08	1.07	1.34	1.44	1.13	1.12	1.00
% from Operation Stage		97.9	97.9	98.7	98.9	98.7	98.4	98.9	98.9
Eutrophication	kg Phosphate Equiv.	4.41E-05	4.34E-05	4.26E-05	5.30E-05	5.69E-05	4.51E-05	4.46E-05	3.97E-05
Normalised Value		1.11	1.09	1.07	1.33	1.43	1.14	1.12	1.00
% from Operation Stage		94.9	94.8	96.6	97.2	96.7	95.8	97.0	97.10
Photo-oxidant Formation	kg Ethene Equiv.	4.06E-06	3.99E-06	3.62E-06	4.40E-06	4.87E-06	3.96E-06	3.72E-06	3.34E-06
Normalised Value		1.22	1.19	1.08	1.32	1.46	1.18	1.11	1.00
% from Operation Stage		75.1	75.2	82.7	85.7	82.8	79.8	84.9	84.12
Aquatic Ecotoxicity	kg DCB Equiv.	1.66E-04	1.64E-04	1.57E-04	1.95E-04	2.11E-04	1.68E-04	1.64E-04	1.47E-04
Normalised Value		1.14	1.12	1.07	1.33	1.44	1.15	1.12	1.00
% from Operation Stage		88.5	88.4	92.0	93.4	92.4	90.8	92.8	92.4
Terrestrial Ecotoxicity	kg DCB Equiv.	0.59064	0.58024	0.57709	0.727096	0.779177	0.60937	0.607395	0.540368
Normalised Value		1.09	1.07	1.07	1.35	1.44	1.13	1.12	1.00
% from Operation Stage		98.5	98.5	99.0	99.2	99.1	98.9	99.1	99.1
Human Ecotoxicity	kg DCB Equiv.	0.001445	0.001409	0.001332	0.001639	0.001783	0.001427	0.001392	0.001235
Normalised Value		1.17	1.14	1.08	1.34	1.44	1.16	1.13	1.00
% from Operation Stage		83.0	83.0	88.0	90.3	88.7	86.6	88.8	89.0

** Normalised value in this table means the ratio between the score value and the lowest value for each impact category*

A similar analysis to the conventional case was produced for the membrane technology with regard to the outputs. For the environmental impact category ***global warming*** the scores, the contribution and the dominant processes for each stage are presented in **Table 5.11**.

Table 5.11. Contribution and dominant processes for global warming (membrane technology)

Scenario	Contribution and Dominant Process		
	Construction	Operation	Decommissioning
1A	0.00387*(1.8)** of which 22% from steel production	0.21690 (98.1) of which 99% from electricity generation	0.0004 00 (0.2) of which 98% from recycling of steel
1B	0.003845 (1.8) of which 22% from steel production	0.21224 (98.0) of which 99% from electricity generation	0.000456 (0.2) of which 98% from recycling of steel
2A	0.002437 (1.1) of which 27% from steel production	0.21212 (98.8) of which 99% from electricity generation	0.000258 (0.1) of which 97% from recycling of steel
2B	0.002452 (0.9) of which 27% from steel production	0.26732 (99.0)of which 99% from electricity generation	0.000260 (0.1) of which 98 % from recycling of steel
3A	0.003272 (1.1) of which 23 % from steel production	0.28588 (98.8) of which 99 % from electricity generation	0.000359 (0.1) of which 97% from recycling of steel
3B	0.003217 (1.42) of which 22.86 % from steel production	0.22351 (98.4)of which 99% from electricity generation	0.000333 (0.2) of which 98% from recycling of steel
4A	0.002118 (0.9) of which 29 % from steel production	0.22342 (98.9) of which 99% from electricity generation	0.000281 (0.1) of which 98 % from recycling of steel
4B	0.001986 (1.0) of which 31 % from steel production	0.19885 (98.9) of which 99% from electricity generation	0.000202 (0.1) of which 96% from recycling of steel

** the units for all global warming scores are kg CO_2 equivalents.*

*** the values in brackets represent the percentage value from the total, overall score for that scenario*

From this table it is clear that for each scenario the scores lie within a narrow range. For global warming all scenarios have the same dominant process for the construction, operation and decommissioning stage. For the construction stage, the production of steel carries the highest environmental burdens; however, methanol production, electricity production, cement production and epoxy production also contribute. For the operation stage, electricity production dominates and for the decommissioning stage the recycling of steel is the dominant process with regard to environmental scores for global warming. Since the operation stage is the stage with the highest contribution (more than 98%) it is clear that the generation of electricity is the process which carries the highest environmental burden for the overall global warming impact category for the membrane technology.

For the impact category of ***ozone depletion*** electricity generation was found to be the main contributor, although the operation stage had a slightly smaller contribution to the overall score when compared to other impact categories. This contribution ranged from 83% (scenario 1A) to 89% (scenario 2B) as can be seen in **Table 5.10**. On average, the proportion which is due to electricity generation is 99% of the scores of the operation stage. For the construction stage the dominant process is steel production.

The construction stage accounts, on average, for about 10% of the total overall ozone depletion scores (scenario 1A with the highest of 13% and scenario 2B with the lowest of 8%). The decommissioning stage has the lowest contribution with an average of 2.5% of the overall score (scenario 1A with the highest of 3.7% and scenario 2B with the lowest, namely 1.8%). The dominant process for the decommissioning stage for this impact category is steel recycling, accounting on average for about 97% of the contribution of the decommissioning stage.

For the environmental impact category of ***acidification*** a similar pattern emerged. The dominant overall process is electricity generation, accounting on average for about 98% of the contribution of the operation stage (see **Table 5.10** for percentage contribution of the operation stage for each scenario). For the construction stage which accounts on average for 1.3% of the overall number (scenario 1A with the highest of 1.9% and scenario 2B with the lowest, namely 1%), the process with the highest contribution is methanol production. However, as can be observed in **Fig. 5.5,** other processes such as cement production and the production of PVC also have significant contributions.

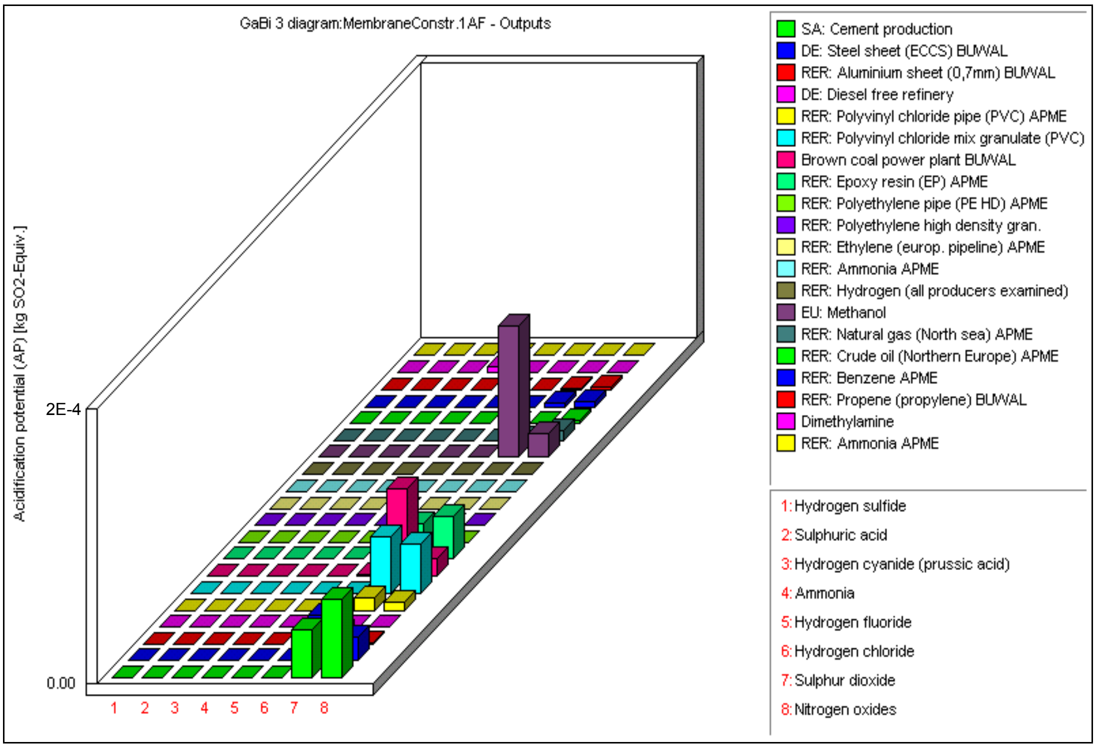


Figure 5.5. Contributions to acidification in the construction stage (membrane technology)

For the decommissioning stage which accounts on average for 0.1% of the overall burden for acidification, the dominant processes is steel recycling (aprox. 97% of the 0.1% overall).

For the environmental impact category of ***eutrophication*** the same pattern is repeated with electricity generation dominating the operation stage and, due to the prominence of this stage, the entire life cycle. The generation of electricity accounts for about 96% of the contribution to this impact by the operation stage. For the decommissioning stage (which accounts on average for 0.3% of the overall) the main contribution towards acidification comes from the recycling of steel (about 97%). For the construction stage the main contributor is the production of cement.

For the environmental category of ***photo-oxidant formation*** (or smog formation) the generation of electricity is the dominant overall process, since it accounts for more than 98% of the environmental burdens of all scenarios in the operation stage. The operation stage accounts for more than 75% of the overall burdens for all scenarios studied (**Table 5.10**). For the construction stage, the dominant process is steel production (accounts for 38% of the environmental burdens of this stage for this category), followed by the production of dimethyl- formamide (20%) and the production of dimethylamine (14%). The last two chemicals are used in the production of the ultrafiltration membranes; dimethylformamide being a co-polymer and dimethylamine being used to produce this co-polymer. The construction stage is responsible, on average, for about 16% (scenario 1A being the highest with 20% and scenario 2B the lowest with 12%) of the overall burdens for photo-oxidant formation. The smallest contribution to this impact category comes from the decommissioning stage, which, on average, accounts for 3% of the overall. Scenario 1A has the highest contribution from this stage with 4% and scenario 2B has the lowest with 2%. The dominant process of this stage is steel recycling, accounting for about 89% of the burdens of this stage for this category.

Toxicity (aquatic, terrestrial and human) scores were produced in a similar fashion as for the other environmental impact categories presented. **Table 5.10** presents the contributions for each scenario and **Table 5.12** presents the dominant processes for each stage for this environmental impact category.

Table 5.12. Average contributions and dominant processes for toxicity

Toxicity	Contribution and Dominant Process		
	Construction	Operation	Decommissioning
Aquatic	7% steel production is the highest contributor	91% electricity generation responsible for 100%	2% recycling of steel responsible for 87%
Terrestrial	1% steel production is the highest contributor	98% electricity generation responsible for 100%	0% recycling of steel responsible for 95 %
Human	7% steel production is the highest contributor	87% electricity generation responsible for 100%	6% recycling of steel responsible for 99 %

It is important to note that the generation of electricity is the overall dominant process, accounting for almost all toxicity environmental burdens in the operation stage, which is the predominant stage. Heavy metals into air and water are the main polluters causing this toxicity. For the decommissioning stage, the recycling of steel has the highest contribution in this stage, with heavy metals into air also being the main polluters.

In conclusion, the generation of electricity is the process which carries the highest environmental burdens for all the impact categories examined for the membrane technology of producing potable water. It is also the process which dominates the operating stage in the life cycle of a membrane plant. In the construction stage, the production of steel is of importance and in the decommissioning stage the recycling of steel. However, the last two life cycle stages account only for little of the overall environmental burdens. The recycling of steel features as a process contributing to the environmental burdens due to the energy needed and the emissions produced. However, recycling of steel saves virgin steel from being used and the environmental burdens associated with producing this virgin steel have not been considered. Therefore, although the recycling of steel is the highest contributor in the decommissioning stage it has a benefit not taken into consideration.

5.3.2 Environmental Scores and the Different Scenarios

Since most of the environmental burdens are traced back to the generation of electricity, it was expected that the scenarios using the highest specific electricity consumption would have the highest environmental scores. This hypothesis is confirmed for all environmental impact categories, with some exceptions such as scenario 1A (**Table 5.13**). **Table 5.10** shows that if values for electricity consumption are the same or very similar for the scenarios considered, other factors differentiate environmental scores and subsequent ranking.

The electricity consumption calculated for the eight scenarios for a membrane plant is due to pumping. Scenario 4B has the lowest specific electricity consumption, because of the way the banks of modules are grouped together. The grouping of 60 high flux modules needs large pumps and large pumps have higher efficiencies than smaller ones. Scenario 4A uses the same type and numbers of modules and the same flux, but a different grouping (banks of 30 as opposed to 60 modules) and needs more electricity for pumping.

5.3.3 Interpretation of the Environmental Scores in Relation to the Contributing Processes

As in the case of the conventional technology, for the membrane technology, the dominant process for all eight scenarios investigated proved to be the generation of electricity. Therefore, it is important to examine how electricity is consumed and generated, and, in general to analyse the energy flows in the system. This was done for one of the eight scenarios investigated, namely for scenario 3A, which is the worst case membrane technology scenario.

From the energy inputs used in this scenario (**Table 5.9** scenario 3A) the operation stage accounts for 2.590 MJ/kL or ca. 98% of the total. Out of this 2.560 MJ/kL energy (or 97% of the total) is needed to produce the 0.751 MJ/kL direct electricity needed in the system. For electricity generation an energy efficiency of about 30% was used in the calculation. It is evident that the bulk of the energy inputs go towards electricity generation and therefore it is important to follow up how the electricity is used in the system.

The electricity requirements for this scenario have been calculated based on the pumping needed in this system (see Friedrich (2001) Appendix 6 for pumps needed for scenario 3A). The highest electricity consumption for pumping is required by the raw feed line (23 961.7 kWh/d or about 63%), followed by the permeate line (12 751.4 kWh/d or about 34%), the reject line (1145.7 kWh/d or 3%) and the backflush line (203.4 kWh/d or 0.5%). Therefore, the highest contribution to the environmental burdens of this technology is traced back to the pumping of raw feed to the filtration modules.

In the case of the membrane technology, another interesting aspect from a design point of view is to look at the burdens of producing the ultrafiltration modules and in particular the burdens of producing the filtration membranes. Since these are small components in the overall burdens of the system, a separate GaBi 3 model had to be made in order to calculate these burdens per mass of module produced for scenario 3A. The technical specifications of this module are presented in Friedrich (2001) (Appendix 5). The materials needed to build these modules have been calculated by up-scaling the module which is currently being produced by the group of Dr. Jacobs, Institute for Polymer Science, University of Stellenbosch. The type of materials and the amounts involved are presented in **Table 5.13**. It must be noted that data on the production of the nitrile lipseal is a major data gap for the production of filtration modules and for the membrane technology in general. However, per kg of module, the nitrile lipseal has the lowest material contribution (6 g nitrile / kg module).

Table 5.13: Quantities needed for one module (250/1500 mm, low flux, 3 240 modules)

Component	*Material*	*Amount/Unit*	*Material per unit*	*Material per module (kg)*	*Total material for all modules (kg)*	*Material (kg/kL)*
Shroud	PVC	1.6 m	8.93 kg	14.288	46293.1	1.34E-04
Netting	PE	234.6 g		0.235	760.1	2.20E-06
Lipseal	Nitrile	213.3 g		0.213	691.1	2.00E-06
Endings	Epoxy	4742 g		4.742	15364.1	4.44E-05
Outlet Saddle	PVC	55 g		0.055	178.2	5.15E-07
Membranes	Polymer	10350 pcs.	1.603 g	16.591	53755.0	1.55E-04

The polymer ultrafiltration membrane is made up for example by co-precipitation of four chemicals (polysulphone, dimethylformamide, polyvinylpyrrolidone and poly (ethylene glycol)). The GaBi 3 process plan for modelling this production process, and the overall production of ultrafiltration modules is presented in **Fig. 5.6**, and **Table 5.14** presents the environmental scores for the overall process.

Table 5.14. Specific environmental scores for the production of ultrafiltration modules (per kg)

Environmental Category	*Score for the production of modules*	*Score for the production of membranes*	*Dominant processes for the production of modules*
Global Warming Potential (kg CO_2-Equiv.)	5.655	3.831 (68%)*	Methanol production Electricity generation
Ozone Depletion Potential (kg R11-Equiv.)	3.94E-8	3.94E-8 (100%)	Propene production (through he release of halon 1301)
Acidification Potential (kg SO_2-Equiv.)	0.045	0.027 (60%)	Methanol production (through emission of SO_2)
Eutrophication Potential (kg Phosphate–Equiv.)	0.003	0.001 (33%)	PVC production (through emission of NO_x)
Photochemical Oxidant Potential (kg Ethene-Equiv.)	0.001	0.0009 (90%)	Production of dimethylamine and dimethylformamide
Aquatic Ecotoxicity Potential (kg DCB-Equiv.)	0.010	0.010 (100%)	Benzene production (through emission of mercury)
Terrestrial Ecotoxicity Potential (kg DCB-Equiv.)	5.546	5.537 (100%)	Electricity generation (through Cd emission)
Human Ecotoxicity Potential (kg DCB-Equiv.)	0.032	0.028 (88%)	Dimethylamine production Benzene production

**The percentages presented are the contribution of the membrane production process to the total score of that category.*

From **Table 5.14** it can be seen that the production of the membranes has a significant contribution to the overall burdens of the filtration module. For some environmental impact categories (i.e. ozone depletion and aquatic ecotoxicity) it is the only contributor.

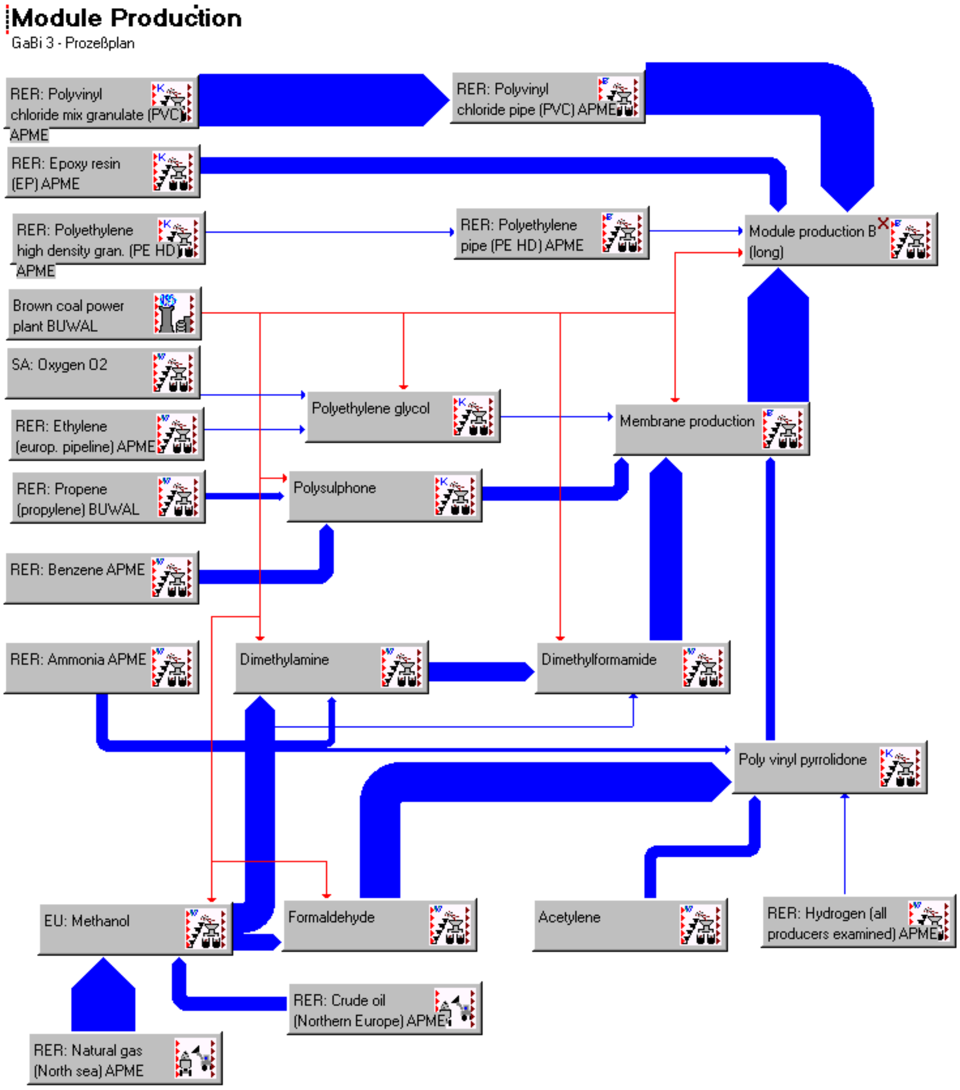


Figure 5.6: Process plan for the production of filtration modules

From a design point of view, for the ultrafiltration modules, this life cycle assessment exercise does not provide straightforward answers, since it does not identify one overall dominant contributor which can be targeted for improvement. Different processes dominate different environmental impact categories, and if environmental improvement for a category is targeted, then those processes contributing to that category should be addressed.

5.4 Comparison of the Two Technologies for Producing Potable Water

For the comparison of the two technologies of producing potable water the worst case scenarios for both technologies have been used. For the conventional technology this meant the scenario with the highest concrete requirements in the construction stage, and for the membrane technology it is scenario 3A as presented in the previous section.

With regard to inputs, the two technologies of producing potable water are compared in **Table 5.15**.

Table 5.15. Material and energy consumption for the two technologies

Stage	***Mass (kg/kL)***		***Energy (MJ/kL)***	
	Conventional Technology	***Membrane Technology***	***Conventional Technology***	***Membrane Technology***
Construction	0.0514	0.0329	0.0873	0.0557
Operation	2.6000	2.5000	2.0670	2.5900
Decommissioning	0.0001	0.0004	0.0009	0.0036
Total	**2.6515**	**2.5333**	**2.1552**	**2.6493**

For both technologies, the operation stage is the most energy and material intensive stage in the life cycle. The values for material and energy consumption for both technologies are comparable, with the conventional technology having a slightly higher mass consumption and the membrane technology having higher energy consumption.

With regard to the outputs, the two potable water producing technologies were compared by using the environmental profiles for the scenarios considered. **Table 5.16** presents this comparison.

As this table above shows, for some impact categories (global warming, acidification and terrestrial ecotoxicity) the conventional technology has lower scores; for the rest of the categories the membrane technology has lower scores. The environmental impact category with the closest scores for both technologies is eutrophication, and the impact category for which the scores differ most is aquatic ecotoxicity.

Table 5.16: Comparison of the environmental profiles for the two technologies

Environmental Impact Category	***Unit***	***Conventional Technology***	***Membrane Technology***
Global Warming Potential	kg CO_2-Equiv.	1.85E-01	2.90E-01
Ozone Depletion Potential	kg R11-Equiv.	3.61E-09	9.55E-10
Acidification Potential	kg SO_2-Equiv.	1.10E-03	1.82E-03
Eutrophication Potential	kg Phosphate–Equiv.	7.40E-05	5.69E-05
Photochemical Oxidant Potential	kg Ethene-Equiv.	1.57E-05	4.87E-06
Aquatic Ecotoxicity Potential	kg DCB*-Equiv.	2.73E-03	2.11E-04
Terrestrial Ecotoxicity Potential	kg DCB-Equiv.	2.59E-01	7.79E-01
Human Toxicity Potential	kg DCB-Equiv.	4.09E-03	1.78E-03

**DCB is 1, 4 dichlorobenzene*.

5.5 Sensitivity Analyses

A series of sensitivity analyses have been performed in order to assess the sensitivity of the environmental scores to the omission of two processes. The sensitivity analyses were performed using the two worst case scenarios as defined in the previous section and environmental scores were recalculated once after transport has been included and once after filtration nozzles have been included.

The difference between the initial scores and the recalculated scores are minimal and therefore the exclusion of transport (for the conventional and membrane technologies) and filtration nozzles for the conventional technology of producing potable water is considered justified. More details regarding these analyses as well as the recalculated scores are presented in Friedrich (2001).

5.6 Comparison with International Studies

This is one of the first published LCA studies in South Africa and the first one in the local water industry. Hence the results of this study could not be compared with similar local or regional results. In the water industry, internationally, LCA has been employed in a few studies ((Grabski et al., 1996) and Emmerson et al. (1995)) mainly in Europe (UK, Sweden, Switzerland and the Netherlands) and mainly for wastewater treatment. There is only one published LCA study investigating the production of potable water by membrane filtration (Meijers et al. ,1998).

The comparison of the results of this study with those of similar studies undertaken internationally is limited due to the different objectives and methodologies and also due to the fact that different processes were investigated. In spite of these differences, a similar result pattern emerged for two international studies. Energy consumption in the operation stage was identified as having a major environmental burden for the treatment of water and the operation stage was seen as the most important stage. This is in accordance with the results of the current study.

5.7 Summary of Results

For both technologies of producing potable water the life cycle of the waterworks is dominated by the operation stage. This stage has the highest material and energy consumption and the highest environmental scores for all the impact categories considered. The decommissioning stage is the least important stage and the construction stage has an intermediate, but minor position.

The most important process to which most of the environmental burdens for producing potable water are traced is the generation of electricity. This process dominates all environmental categories for the operation stage and, because of the predominance of this stage, it dominates the entire life cycle for water production for both technologies considered.

When comparing the environmental scores for the two technologies the values involved are of the same magnitude and therefore, from an environmental point of view, the two technologies are comparable. When comparing the results of this study with other similar studies some common trends have been observed, i.e. the importance of energy consumption in the operation stage and the importance of the operation stage to the life cycle of the waterworks.

The exclusion of transport was proven to be a valid assumption for both technologies investigated. The same is valid for the exclusion of filtration nozzles for the conventional technology.

CHAPTER 6
CONCLUSION AND RECOMMENDATION

This chapter is the second part of the interpretation phase as set by the ISO 14040 standard and it presents the conclusion of this study, the recommendations, a list of publications and technology transfer actions emerging from this research and an assessment on the realisation of the project aims.

6.1 Conclusion

This research should be seen as a LCA base-line study for the production of potable water and it has investigated, by using LCA methodology, two technologies to produce such water. The conventional method has been employed at Wiggins Waterworks, Durban since 1984. It is a tried and tested method which has been continuously improved. For this study operational data from a period of 28 months was used. The membrane method is based on a developing technology and so far it has been used in three pilot plants around the country. One of these pilot plants is situated at the Wiggins Waterworks Process Evaluation Facility (PEF). This location gave the unique opportunity for a LCA comparison of the two methods, since the quality of the incoming water is the same. However, there is no ultrafiltration membrane facility of the size required for a comparison and a virtual plant had to be up-scaled, and in this process various assumptions had to be made. The authors are aware that these assumptions may introduce a higher margin of error for the ultrafiltration membrane technology. For this method there was no design optimisation undertaken during the up scaling.

The LCA methodology employed in this study follows the ISO 14040 series of standards which prescribe 4 phases: goal and scope definition, inventory analysis, impact assessment and interpretation. For the impact assessment phase the CML (Center for Environmental Science, University of Leiden) methodology was used. In conducting this study the GaBi 3 software tool played an important role and partially pre-empted the methodological choices, since it is programmed to use the above mentioned methodology in the impact assessment phase.

For both water treatment technologies the life cycle of the waterworks is dominated by the operational stage. This stage has the highest material and energy consumption and the highest environmental scores for all the impact categories considered. The decommissioning stage is the least important one and the construction stage has an intermediate, but minor position. Therefore, for future waterworks, if any environmental trade-off between life stages is possible, it should be encouraged towards decreasing the environmental burdens of the operation stage. For example, the building of an additional tank in the construction phase should be encouraged, provided it decreases the overall energy consumption in the operation stage.

The most important process to which most of the environmental burdens for producing potable water are traced is the generation of electricity from coal. This process dominates all environmental impact categories for the operation stage, for both technologies considered. Because of the predominance of the operation stage it dominates the entire life cycle of the waterworks. The focusing capacities of this environmental tool are highlighted by these results, LCA being able to identify major environmental contributors in a complex, interconnected system. By targeting these major contributors, the overall environmental performance of the system can be improved in the most efficient manner. LCA also provides a holistic view of environmental impacts and that is shown with regard to these results. Electricity is an off-site environmental burden and the negative impacts associated with this process are invisible to the operators of the water treatment plant, therefore, this power source is perceived as clean and attention is given to more ‘obvious’ emissions like air emissions and sludge discharges.

When comparing the environmental scores for the two potable water producing technologies, the values involved are of the same magnitude and therefore, from an environmental point of view, the two technologies are comparable. However, it is not possible to recommend one technology above the other because of the mixed quality of data used and because the environmental scores are very close.

The sensitivity analyses performed proved that the exclusion of transport at the beginning of the study was a valid assumption for both technologies investigated. The exclusion of filtration nozzles for the conventional technology also proved to be valid.

When comparing the results of this study with those of similar international studies, a common pattern can been observed. The operational stage is the dominant stage of a waterworks and energy (or electricity) consumption in this stage is seen as having a major contribution to the environmental burdens of the overall water treatment processes.

In this study the main difficulties were experienced in the data gathering stage and they have been overcome by employing overseas data and by using calculations. These difficulties were related to the lack of availability of local data; however, with increasing demand for LCA studies in South Africa more data will became available and further LCA studies should be easier to undertake. There is a strong movement within the LCA community towards simplification of the LCA methodology. This will make LCA studies more accessible for South African companies and more LCA studies will be initiated. In creating this demand and increasing awareness about LCA as an environmental tool, the Pollution Research Group and this study play an important role through the educational outcomes of this project. As a result of this study, to date, two companies have introduced LCA. Natal Portland Cement are updating and completing the initial calculations done for them in 1999 during the data collection for cement production. The results will be presented in the Cement and Concrete Institute newsletter, which is due to be published in October 2001. Umgeni Water will take over this study and they plan to replicate and expand it for other waterworks under their control.

6.2 Recommendation

There are two types of recommendations pertinent to this study, namely recommendations for environmental improvement based on the results obtained and recommendations for further research in the field.

6.2.1 Recommendations for Environmental Improvement

The majority of environmental burdens for producing potable water are traced back to the consumption of electricity for the operation of waterworks. Therefore, the main recommendation emerging from this study is the need to increase electricity efficiency during operation.

For Wiggins Waterworks, a first step towards better use of electricity would be monitoring and targeting electricity consumption. This can be achieved on the site by installing simple electricity measuring devices (starting with high consumers of the electricity) and by keeping record of consumption values. The next step would be to optimise all processes (starting with the most electricity consuming ones) and make them more energy efficient. Ozonation should be a process to be targeted and especially the ozone destruction units since from the data collected they seem to need more electricity as the ozone generators.

For the membrane plant, choosing a design option which has the lowest electricity consumption is the most important step which should be undertaken. Efficiency of pumping is an issue which should be followed, since it impacts the most on the overall electricity consumption. Since most of the pumping is due to the pressures required in the system an investigation into pressure needs and pressure loss is recommended. Smaller improvements to the overall environmental performance of ultrafiltration modules can be achieved by designing these modules for recycling; this means a design which makes the separation of individual module materials possible. Further research applications of membrane processes in the production of potable water should be encouraged, as the membrane processes involved in this study compare favorably with conventional water treatment processes. A compromise between membrane hardware (capital) and energy consumption (operating costs) needs to be undertaken for using both financial and environmental considerations in guiding the development of the South African membrane technology. Since the membrane technology is developing, an ongoing LCA service should be provided to the membrane researchers involved in this development. This will allow the calculation and comparison of environmental burdens of the different prototypes of membrane filtration plants making it possible to choose the most environmentally friendly option.

6.2.2 Recommendations for Further Research

Further research is needed to make the impact assessment of the LCA more relevant to the local environmental conditions. As mentioned in the methodology chapter, there is a need to develop environmental impact categories to reflect local environmental problems, such as scarcity of water and salination. Therefore, the recommendations in this area focus on an array of measures aimed to develop these impact categories in a similar fashion to the ones already established in the LCA methodology (e.g. global warming, acidification and eutrophication). With regard to the scarcity of water, the measurement of water consumed by processes may be used as an initial rough assessment of the water intensity of processes. However, one must be aware that imported goods may be manufactured in countries where water is plentiful, therefore a geographical distinction between the water consumed may prove important. For salinity, however, existing research needs to be reviewed and the chemical species contributing to this environmental problem have to be identified. In a next step characterisation (or equivalency) factors should be developed.

This study is a comparative study of two technologies involved in the production of potable water. It is not a complete study for the entire cycle for potable water. The abstraction of water, the transport of raw water to waterworks and the delivery of treated water to consumer are not included when calculating environmental scores and were not researched in this study. Hence, further research should include these aspects in order to calculate the full environmental burdens of potable water production.

Further research projects should target the improvement of energy efficiency of ozonation (ozone production and destruction) and of sludge treatment, since these are the most energy intensive processes for the conventional technology.

Umgeni Water expressed an interest to carry this study further for the conventional technology. It is recommended that for a more detailed study the initial data has to updated and validated and more complete measurements should be sought with regard to electricity consumption values (e.g. for ozonation).

REFERENCES

Bengtsson M., Lundin M. and Molander S., (1997) **Life Cycle Assessment of Waste Water Systems**, Technical Environmental Planning Report, Chalmers University of Technology, Goteborg, Sweden.

Chevalier J. and Rousseaux P. (1999) Classification in LCA: Building a Coherent Family of Criteria, **The International Journal of Life Cycle Assessment**, **4** (6), 352-356.

Christiansen (ed.), (1997) **Simplifying LCA: Just a Cut?** Final report SETAC (Society for Environmental Toxicology and Chemistry) Europe LCA Screening and Streamlining Working Group, SETAC Europe, Brussel, Belgium.

Consoli F, Allen D., Boustead I., Fava J., Franklin W., Jensen A. A., de Oude N., Parrish R., Perriman R., Postlethwaite D., Quay B., Sequin J., Vigon B., (1993) **Guidelines for Life-Cycle Assessment: A Code of Practice**, Society for Environmental Toxicology and Chemistry, Brussel, Belgium.

Curran, M. A. (ed.), (1996) **Environmental Life Cycle Assessment**, McGraw-Hill, New York, USA.

Department of Environmental Affairs and Tourism, (2000) **White Paper on Integrated Pollution Control and Waste Management, Government Gazette,** 417 (20978), 17 March 2000, South Africa.

Earth Summit '92, Agenda 21, (1992), The United Nations' Conference on Environment and Development, Rio de Janiero, Regency Press, London, UK.

Emmerson R.H.C., Morse G.K. and Lester J.N., (1995) The Life-Cycle Analysis of Small-Scale Sewage Treatment Processes, **Journal of the Chartered Institution of Water and Environment Management**, **9** (3), 317-325.

Eskom Environmental Report, (1999) Eskom Corporate Environmental Affairs, Johannesgurgh, South Africa. The report is also available on the internet at the following address: http://www.eskom.co.za.

Finnveden, G., (2000), On the Limitations of Life Cycle Assessments and Environmental Analysis Tools in General, **The International Journal of Life Cycle Assessment**, **5** (4), 229-238.

Forbes, P., (1999) **The Use of Life Cycle Assessment in the Evaluation of Environmental Performance in the Base Metal Refining Industry**, University of Cape Town, Masters Thesis in the Department of Chemical Engineering, Cape Town, South Africa.

Friedrich, E. (2001) **The Use of Environmental Life Cycle Assessment for the Production of Potable Water,** Masters Thesis (submitted), School of Chemical Engineering, University of Natal, Durban, South Africa.

Frischknecht R., (1993) **Oekobilanz – Motivation – Moeglichkeiten – Grenzen**, Unterlagen fuer den Vertiefungsblock Oekobilanzen 1993.04.23 – 24, NDS Umwelttechnik, Vaduz, Lichtenstein.

Grabski C., Fahner S., Buhrer H. and Leuenberger H., (1996) Oekobilanz einer Klaeranlage, **Abwasserreinigung**, 6, 1053-1056.

Graedel T. E., (1998) **Streamlined Life-Cycle Assessment**, Prentice Hall, New Jersey, USA.

Graedel T.E. and Allenby B.R., (1995) **Industrial Ecology**, Prentice Hall, New Jersey, USA.

Guinee, J.B. (ed.), Goree, M., Heijungs R., Huppes, G., Keijn R., de Haes U., van de Voet E., Wrisberg M.N., (1998) **Environmental Life Cycle Assessment**, Draft Report on LCA Backgrounds (8 Ocober, 1998), Center of Environmental Science (CML), Leiden University, Leiden, The Netherlands.

Hauschild, M. and Wenzel, H., (1997) **Environmental Assessment of Products – Volume 2: Scientific Background**, Chapman & Hall, London, UK.

Heijungs, R. (ed.) (1992) **Environmental Life Cycle Assessment of Products – Guide**, Center for Environmental Science, University of Leiden, Leiden, The Netherlands

ISO 14040, (1997) **Environmental Management – Life Cycle Assessment – Principles and Framework**, South African Bureau of Standards, Pretoria, South Africa.

ISO 14041, (1999) **Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis**, Geneva, Switzerland.

ISO 14042, (1997) **Environmental Management – Life Cycle Assessment –Life Cycle Impact Assessment**, ISO/CD Draft, Geneva, Switzerland.

ISO 14042, (2000) **Environmental Management – Life Cycle Assessment –Life Cycle Impact Assessment**, Geneva, Switzeerland.

ISO 14043, (2000) **Environmental Management – Life cycle assessment – Life cycle Interpretation**, Geneva, Switzerland.

Jacobs E.P., Botes J.P., Bradshaw S.M. and Saayman H.M., (1997) Ultrafiltration in Potable Water Production, **Water SA**, **23** (1), 1-6.

Jacobs E.P. and Leukes W.D (1996) Formation of an Externally Unskinned Polysulfone Capillary Membrane, **Journal of Membrane Science**, **121**, 149-157.

Jacobs E.P., Institute for Polymer Science, University of Stellenbosch, Personal Communication, 10 January 2000

Jensen, A. A., Elkington, J., Christiansen, K., Hoffmann, L., Moller, B. T., Schmidt, A., van Dijk, F., (1997) **Life Cycle Assessment (LCA) – A Guide to Approaches, Experiences and Information Sources**, Report to the European Environmental Agency, Copenhagen, Denmark.

Krozer J. and Vis J.C., (1998) How to Get LCA in the Right Direction? **Journal of Cleaner Production**, **6** , 53-61.

Kloepffer W., (1997) Life Cycle Assessment – From the Beginning to the Current State, **Environmental Science & Pollution Research**, **4** (4), 223-228.

LCA-NORDIC, (1995), **Technical Reports No 1-9**, Nordic Council of Ministers (TemaNord:502), Copenhagen, Denmark.

Lindeijer, E., (1996) Part IV: Normalisation and Valuation in Udo de Haes (ed.) **Towards a Methodology for Life Cycle Assessment**, SETAC, Brussels, Belgium.

Lindfors L-G., Christiansen K., Hoffman, L., Virtanen Y., Juntilla V., Hansen O.J., Ronning A., Ekvall T. and Finnveden G,. (1995) **Nordic Guidelines on Life Cycle Assessment**, Nordic Council of Ministers, Copenhagen, Denmark.

Mannion A.M., Bowlby, S.R., (eds.) (1995) **Environmental Issues in the 1990s**, John Wiley & Sons, Chichester, UK.

Meijers K., Verberne A.J.P. and Koreman E.A., (1998) Levenscyclusanalyse van Membraanfiltratie, **H_2O**, 21, 33-36.

Middleton B., (1998) Water Audit – The Resource, The Future, Some Solutions, **Water Sewage and Effluent**, **18** (1), 20-22.

Miller T. G., (1997) **Living in the Environment**, Wadsworth Publishing, Belmont, California, USA.

Nazaroff W.W. and Alvarez-Cohen L., (2001) **Environmental Engineering Science**, John Wiley & Sons, New York, USA.

Nozaic D.J., Freese S.D. and Thompson P., (2000) **Long Term Experience in the Use of Polymeric Coagulants for Coagulation and Flocculation at Umgeni Water**, IAWQ 6th International Conference on Particle Removal, Durban, South Africa, February 2000.

Oosterom H.A., Nederlof M.M., Galjaard G. and Schippers J.C., (1998) **Feasibility of Micro-and Ultrafiltration for the Treatment of Raw Water Surface Water; Results of Various Pilot Studies in the Netherlands**, Poster presented at the Conference on Membranes in Drinking Water and Industrial Water Production, Amsterdam, The Netherlands, September 21-24 1998.

Our Common Future, 1987, World Commission on Environment and Development Report, Oxford University Press, New York, USA.

Overcash, M., Kim, S. and Jimenez-Gonzales, C., (2000) Methodology for Developing Gate-to-Gate Life Cycle Inventory Information, **The International Journal of Life Cycle Assessment**, **5** (3), pgs. 152-159.

Owens, W. J., (1997) Life Cycle Assessment – Constraints on Moving from Inventory to Impact Assessment, **Journal of Industrial Ecology**, **1** (1), 37-49.

Owens, W. J., (1999) Why Life Cycle Impact Assessment is Now Described as an Indicator System, **The International Journal of Life Cycle Assessment**, **4** (2), 81-86.

Park H.S., Labys W.C., (1998) **Industrial Development and Environmental Degradation**, Edward Elgar Publishing, Cheltenham, UK.

Pryor M. J., Jacobs E.P., Botes J. P. and Pillay V.L,. (1998) A Low Pressure Ultrafiltration Membrane System for Potable Water Supply to Developing Communities in South Africa, **Desalination**, **119**, 103-111.

Rice, G., Clift, R. and Burns, R., (1997) LCA Software Review: Comparison of Currently Available European LCA Software, **The International Journal of Life Cycle Assessment**, **2** (1), 53-59.

Stinnes I. A., Page, D. C., Fleischer, G., (1996) Comparison of LCI Studies in South African and Germany, **International Journal of Life Cycle Assessment**, **1** (2), 110 – 112.

Thompson P., (2000) **Wiggins Waterworks Process Design Description**, Umgeni Water Internal Report, Science Services Division, Umgeni Water. Pietermaritzburgh, South Africa.

Thompson P., Umgeni Water, Personal Communication. 14 February 2000.

Umgeni Water Public Affairs Department, (1998), Pamphlet on Wiggins Waterworks.

UNEP, (1996) **LCA What it is and how to do it**, UNEP Publications, Paris, France.

UNEP Website: http://www.unepie.org

Urban-Econ, (2000) **The Economic Cost Effects of Salinity – Volume 1**, Report to the Water Research Commission and the Department of Water Affairs and Forestry, Pretoria, South Africa (WRC Report No: TT 123/00).

Van der Merwe A., Department of Transport, Personal Communication, 5 June 2000.

Van Duuren F.A., (1997) **Water Purification Works Design**, Water Research Commission, Pretoria, South Africa

Vigon B.W., Tolle D.A., Cornaby B.W., Latham H.C., Harrison C.L., Boguski T. L., Hunt R.G. and Sellers J.D., (1993) **Life Cycle Assessment: Inventory Guidelines and Principles**, United States Environmental Protection Agency, Office of Research and Developemnt Washington D.C., USA (EPA/600/R-92/245).

Weidema P. B., (1997) **Environmental Assessment of Products**, The Finnish Association of Graduate Engineers, Helsinki, Finland.

Welford R., (1995) **Environmental Strategy and Sustainable Development – The Corporate Challenge for the 21st Century**, Routledge, London, UK.

Wenzel, H., Hauschild, M. and Alting, L., (1997) **Environmental Assessment of Products – Volume 1: Methodology, Tools and Case Studies in Product Development**, Chapman & Hall, Publishers, London, UK.