Environmental Life cycle assessment of water use in South Africa: The Rosslyn industrial area as a case study

Landu Landu

Submitted in fulfilment of the academic requirements for
the degree of

MASTER OF APPLIED SCIENCES (ENVIRONMENTAL TECHNOLOGY)

in the

FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

UNIVERSITY OF PRETORIA

PRETORIA

0002

JUNE 2005

Motto

***"The tragedy of life is not by not reaching a goal,
but not having a goal to reach".***

(Nathalie du Toit, 2005)

PREFACE

Life Cycle Assessment (LCA), as an application tool in the South African context, is very limited with regard to the availability of data. This is due to the reluctance of South African companies to provide a list of input data. Despite this reluctance and accompanying limitations, there is a growing interest in LCA research in South Africa, especially with the incorporation of Life Cycle Engineering in the Department of Engineering and Technology Management at the University of Pretoria and in the Pollution Research Group in the University of Natal's School of Chemical Engineering as well number of companies that are already using this tool. The Water Research Commission of South Africa (WRC), with its mandate to support water research and development, provides the necessary funds for LCA applications with regard to water resources.

Through this study, I gained experience in the development and application of LCA as an environmental tool for industry and business. I hope that this work provides the necessary information and assistance on how environmental life cycle assessment, as an environmental management tool, is applied and that it promotes the application of LCA in a sustainable development context to address environmental concerns in South Africa.

This research was carried out in the University of Pretoria's Department of Engineering and Technology Management (Life Cycle Engineering) under the supervision of Dr Alan Brent and funded by the WRC.

Many people have helped me by giving of their precious time and providing valuable inputs, which has been remarkable, particularly at Rand Water (Zuikerbosch, Palmiet and at the head office) and at the City of Tshwane Metropolitan Municipality. I am grateful to all those who have been involved in this study.

Special thanks go to my supervisor, Dr Alan Brent, for his patience, guidance and advice; to Carin Labuschagne for her encouragement and management of this research project; and finally to my wife, Chouchouna Landu, for her moral and spiritual support.

The financial support of the WRC for this research is gratefully acknowledged.

Dissertation summary

Environmental LCA of water use in South Africa: The Rosslyn industrial areas a case study

LANDU LANDU

SUPERVISOR: Dr AC Brent

DEPARTMENT: Department of Chemical Engineering
Faculty of Engineering, Built Environment and
Information Technology, University of Pretoria

DEGREE: Masters of Applied Sciences (Environmental Technology)

KEYWORDS: environmental life cycle assessment (LCA); life cycle impact analysis (LCIA); limitations; water use; water supply; life cycle; environmental burdens; potable water production procedure; life cycle inventory; methodology; LCIA framework; water resources; toxicity potential; environmental improvements; conservation of water resources; unit processes; water supply system; life cycle assessment; Rosslyn industrial area; South Africa.

International LCA literature indicates that little data is available pertaining to potable water production and supply, in particular with respect to the environmental burdens generated within the system. This study aims to investigate and assess the environmental burdens associated with the potable water supply to an industrial area (Rosslyn, north of Pretoria, in the Tshwane Metropolitan Municipality). The procedure, as well as the assessment of the environmental impacts of a life cycle, is dependent on a comprehensive life cycle inventory (LCI) of the evaluated system. Water use is included in LCIs, which are incorporated into the LCIA procedure, as it reflects a direct extraction from available resources.

The water supply system diagram has been developed and data was collected, treated and analysed in the inventory analysis phase. The study closely followed the four phases as stipulated in the International Organization for Standardization (ISO 14040 series of standards) for conducting LCAs, including:

- goal and scope definition;
- LCI analysis;
- LCIA; and
- Interpretation, conclusions and recommendations.

The methodology used in the impact assessment phase was the introduced LCIA framework for South Africa in order to determine the extent of different environmental impacts. The inventory analysis, conforming to the scope of the study, provided an overall inventory of energy and other resource requirements, emissions to water and air, dust fallouts and solid or liquid wastes for the system under study.

By using this methodology and by tracing all unit processes involved in the potable water supply system, the main contribution to the environmental burdens imposed on the potable water supply system was found to be the extraction of the required water from nature to supply potable water to Rosslyn.

The toxicity potential impacts on water resources, mainly due to the electricity required for the water supply system, are of minor importance. This conclusion is valid for the system investigated, and as a result, the recommendations for environmental improvements should focus on water losses that must be addressed foremost. What is required at this stage is strategic planning regarding the extraction, use and conservation of water resources. Furthermore, to optimise all processes of water extraction, and to make them more efficient, electricity and other energy inputs are also of importance, albeit to a lesser extent.

Table of contents

List of tables

List of figures

List of Acronyms

ARC:	Agriculture Research Council
CML:	Institute of Environmental Sciences, the Netherlands
CP:	Cleaner Production
DEAT:	Department of Environmental Affairs and Tourism
DWAF:	Department of Water Affairs
EIA:	Environmental Impact Assessment
EIO:	Economic Input-Output LCA
EIOLCA:	Economic Input-Output Life Cycle Assessment
EMS:	Environmental Management System
EPS:	Environmental Priority Strategies
ISO:	International Organization for Standardization
IWMI:	International Water Management Institute
LCA:	Life Cycle Assessment
LCAI:	Life Cycle Assessment Interpretation
LCI:	Life Cycle Inventory
LCIA:	Life Cycle Impact Assessment
LCM:	Life Cycle Management
REPA:	Resource and Environmental Profile Analysis
RII:	Resource Impact Indicator
RMEE:	Relative Mass-Energy-Economic method
SALCA:	South African Life Cycle Assessment (Regions)
SETAC:	Society of Environmental Toxicology and Chemistry
SPOLD:	Society for the Promotion of Life Cycle Assessment Development
UAW:	Unaccounted for Water (losses)
UNFCCC:	United Nations Framework on Climate Convention
UNEP:	United Nations Environmental Program
WMA:	Water Management Areas
WRC:	Water Research Commission

Chapter 1: Introduction and background to the study

1.1 *Water use in South Africa*

1.1.1 Rural and urban water use

The WRC report (1997:27) states that the steadily increasing demand for water, in conjunction with limited supplies, has made water use the driving force of the urban and rural water cycle. The main challenge now is to devise ways and means of convincing consumers and suppliers of the need to conserve water at all times.

Basson *et al* (1997:10) showed that water use in South Africa is still dominated by irrigation, which represents about 54% of the total water use in the country, most of which is used consumptively. Much of the irrigation also occurs in the drier parts of the country, such as the Orange River Basin, the Crocodile (Limpopo) River Basins, the Lower Vaal Basin, the Sunday/Fish River Basins, and the Western Cape areas. Afforestation, which uses large quantities of water before it reaches streams or rivers (about 8% of the total), is more dominant in the wetter, eastern parts of the country. The domestic and the general urban use of water constitutes about 11% of the total usage, which is larger in magnitude than the approximately 8% currently being used by the mining sector and some separate large industries outside the municipal areas. The latter is representative of users such as Sasol, Eskom and Sappi, while smaller and general industries are included under urban water use.

1.1.2 Related environmental problems

In the Water Engineering Symposium Report (1994:61), it is emphasised that, I quote “As a developing country, South Africa has special environmental problems. The increasing population and the need for rapid urban development are putting the natural environment under great stress.

1.1.2.1 Environmental impacts

Based on the present trends in water use and population growth, this is accompanied by a decrease in water quality and environmental health risk.

In 1994 a common view emerged from the Water Engineering Symposium (1994:62) held in South Africa, that water is a central concern in development and social upliftment through the roles of water supply and sanitation in the improvement of public health. After the provision of basic shelter, these are probably the most pressing infrastructural needs. Urbanisation, water supply and sanitation, while effecting essential modifications to the environment for the benefit of people, also have negative environmental impacts. Both pollution and the physical changes in hydrological regime resulting from such developments can have severe consequences for natural aquatic systems (Water Engineering 1994:62).

South Africa is a semi-arid country with sporadic wet and dry periods. Its water resources are therefore vital. This has resulted in the national development of objectives with respect to the economic activities of the country, the health and the prosperity of its people, and the sustenance of natural heritage (Basson *et al.* 1997:6). There is still a special management concern to improve and address the environmental health risk in a sustainable manner and to develop standards for beneficial water use where environmental problems occur.

1.1.2.2 Water scarcity

The Review of Water Resources Statistics 2001 (as cited in Ochieng and Otieno 2004:120) has indicated that South Africa, currently categorised as a water-stressed country, is forecasted to experience physical water scarcity by the year 2025 with an annual freshwater availability of less than 1 000m^3 per capita. With the trends in population growth and its attributes, combined with the ongoing pollution of the available water sources, there is bound to be increased pressure on the available water, probably resulting in increased conflict over its allocation and further pressure on this resource, leading to scarcity. South Africa, for example, is a semi-arid country (65% of the country is classified as being semi-arid), in which the average rainfall of 450 mm per annum is well below the world average of about 860 mm per annum [6]. As a result, South Africa's water resources are, in global terms, scarce and limited in extent (RSA, 2002).

The International Water Management Institute (IWMI) (1996:19) estimates that in 2025 the country will be among the countries in the world that will experience a physical water scarcity scenario with an annual freshwater availability of less than 1 000m^3 per capita (the index for water scarcity). The natural availability of water across the country is also uneven. This is compounded by a strong seasonality of rainfall. Currently 11 of the 19 water management areas (WMAs) (catchment based) in the country are facing a water deficit where the need for water exceeds its availability, whilst a surplus still exists for the country as a whole.

An analysis by the Department of Water Affairs and Forestry (DWAF) through the National Water Resource Strategy (2002) shows that looking forward to 2025 several additional WMAs will experience a water deficit, even if further potential infrastructure development is factored into the development of infrastructure. This is in itself an expensive option and therefore the efficient use of currently available water resources must be improved [8].

1.2 Background to Life Cycle Assessment

A literature survey was used as part of this dissertation to summarise and highlight the theoretical LCA information sources in order to give a background to the concepts and methods employed in this study.

1.2.1 Brief history of Environmental Life Cycle Assessment

According to the Society of Environmental Toxicology and Chemistry (SETAC) workshop report (1990:3), the research on various elements of LCA has roots as far back as the 1960s. The LCA studies originated to analyse raw material use and energy demands associated with production systems in the late 1990s. US researchers developed the Resource and Environmental Profile Analysis (REPA) model. Independently, researchers in Britain, Sweden and Switzerland also developed energy and material models. The REPA model and other LCA studies in the late 1960s and early 1970s began to consider a wide range of environmentally relevant factors.

Interest in LCA studies waned somewhat as traditional energy supplies appeared to become more stable. In the report of the SETAC (LCA) Impact Assessment Workgroup (1997:20), findings showed that renewed interest in LCA methodologies had been rekindled in the late 1980s through solid waste concerns. When solid waste became a worldwide issue in 1988, the LCI analysis technique emerged as a tool for analysing environmental problems. Although focusing on energy characteristics, these thoughts included estimates of gaseous emissions, solid waste and effluent from water sources.

Pressure from the Green Movement promoted recycling efforts. As a result, discharges gaseous, solid and liquid emissions were routinely added to energy, raw material and solid waste considerations. The last few years have seen a significant increase in research activity in this area. Developed under the REPA model, these early studies became the model for the development of the modern LCA (Fava (ed) *et al*., 1994:4).

LCA is now becoming an important, widely accepted tool of the technologist, designer and planning analyst. The 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 centres and universities, work for the International Organization for Standardization (ISO), especially the ISO 14040 series and the Society for the Promotion of Life Cycle Assessment Development (SPOLD) (Friedrich and Buckley, 2002:6).

1.2.2 Overview of LCA methodology

1.2.2.1 Definition of Environmental Life Cycle Assessment

LCA is an objective process designed to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and waste released into the environment; to assess the impact of energy and materials and released into the environment in order to evaluate and implement opportunities to affect environmental improvements (Fava (ed) *et al*., 1994:1).

A framework for executing an LCA study is well documented in the ISO publications (ISO, 1998:4). In general, a complete LCA study of a product system must consist of four phases (ISO, 1998:5):

- Goal and scope definition: describes the application or specific interest and indicates the target group. A detailed description of the system to be studied is included, providing a clear delimitation of scope, periods and system boundaries.
- Life Cycle Inventory (LCI) analysis: quantifies the environmentally relevant inputs and outputs of the studied system, which is essentially a mass and energy balance of each unit (or smaller) or process within the larger system. ISO has provided a general framework for the inventory analysis (ISO, 1998:8).
- Life Cycle Impact Assessment (LCIA): quantifies the environmental impact potential of the inventory data.
- Interpretation and improvement analysis: where options are identified and evaluated to reduce the environmental impacts of the studied system.

1.2.2.1.1 The LCIA procedure

The exact procedure followed to execute the environmental impact assessment (EIA) phase of an LCA is not stipulated clearly (ISO, 2000:10), and the scientific community is in disagreement on the methodology to be followed (Rebitzer *et al.*2001:187) and the results that are obtained from different approaches (Finneven et *al.,* 2000:229). The consequence has been the formation of an international LCIA workgroup, which forms part of the United Nations Environmental Program (UNEP) and SETAC global life cycle initiative (UNEP *Global Life Cycle Initiative,* 2003). The initiative was formally launched in April 2002. The LCIA workgroup aims to develop an internationally acceptable framework (including terminologies and data) for the LCIA phase of LCAs and Life Cycle Management (LCM) in general over the next few years. Of particular importance is the development of satisfactory LCIA procedures for the users thereof, i.e. business and government decision makers.

The complexity of the LCIA procedure lies in the cause-effect chains linking discharges (emissions, waste and effluent) and resource depletion to their consequences (Finneven *et al.,* 1992). These cause-effect chains show that environmental impacts can be described at different levels of effects. Table 1 uses the example of greenhouse gas release to show the possible different levels of effects (Baumann and Tillman, 1999).

Level	Cause-effect
Activity	Combustion processes, e.g. electricity generation from coal
Pollutants emitted	Carbon dioxide (CO_2), methane (CH_4), etc.
Primary effect	Radiative forcing, i.e. absorption of thermal infra-red radiation into the atmosphere
Secondary effect	Increase in global temperature
Tertiary effect	Ice-melting, rising sea levels, change in weather patterns
Further effects	Specific changes in ecosystems

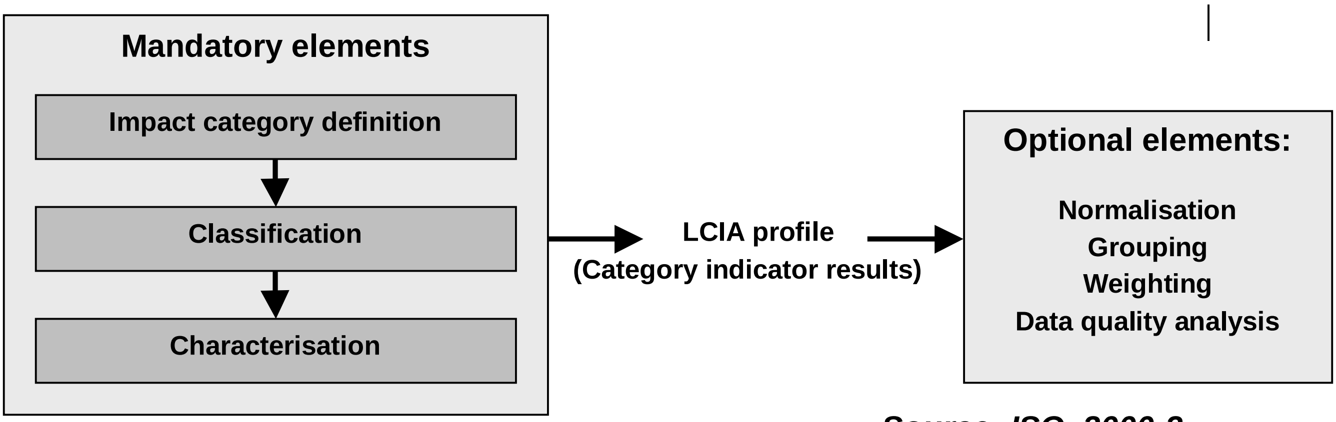
Source: Baumann and Tillman, 1999

Table 1: Different levels of effect due to greenhouse gas releases

Due to the intricacy of evaluating the cause-effect chain of each environmental problem, LCIA methods have been published (in book, university thesis and company report format) that can be used by decision makers to obtain LCIA results in the short term without necessarily understanding all the underlying environmental scientific principles. The following five methods are most commonly used in the manufacturing industry of South Africa (Brent and Hietkamp, 2003: 28):

- Institute of Environmental Sciences (CML) from Leiden University, the Netherlands (Guinee JB *et al.,* 2001: 43).
- Ecopoints from BUWAL, Switzerland (Braunschweig A *et al*. 1998:1).
- Eco-indicators 95 (Goedkoop M et al.,1996:1) from Pré Consultants, the Netherlands.
- Eco-indicators 99 (Goedkoop M et al.,2000:1) from Pré Consultants, the Netherlands.
- EPS from Chalmers University of Technology, Sweden (Steen B 1999:20).

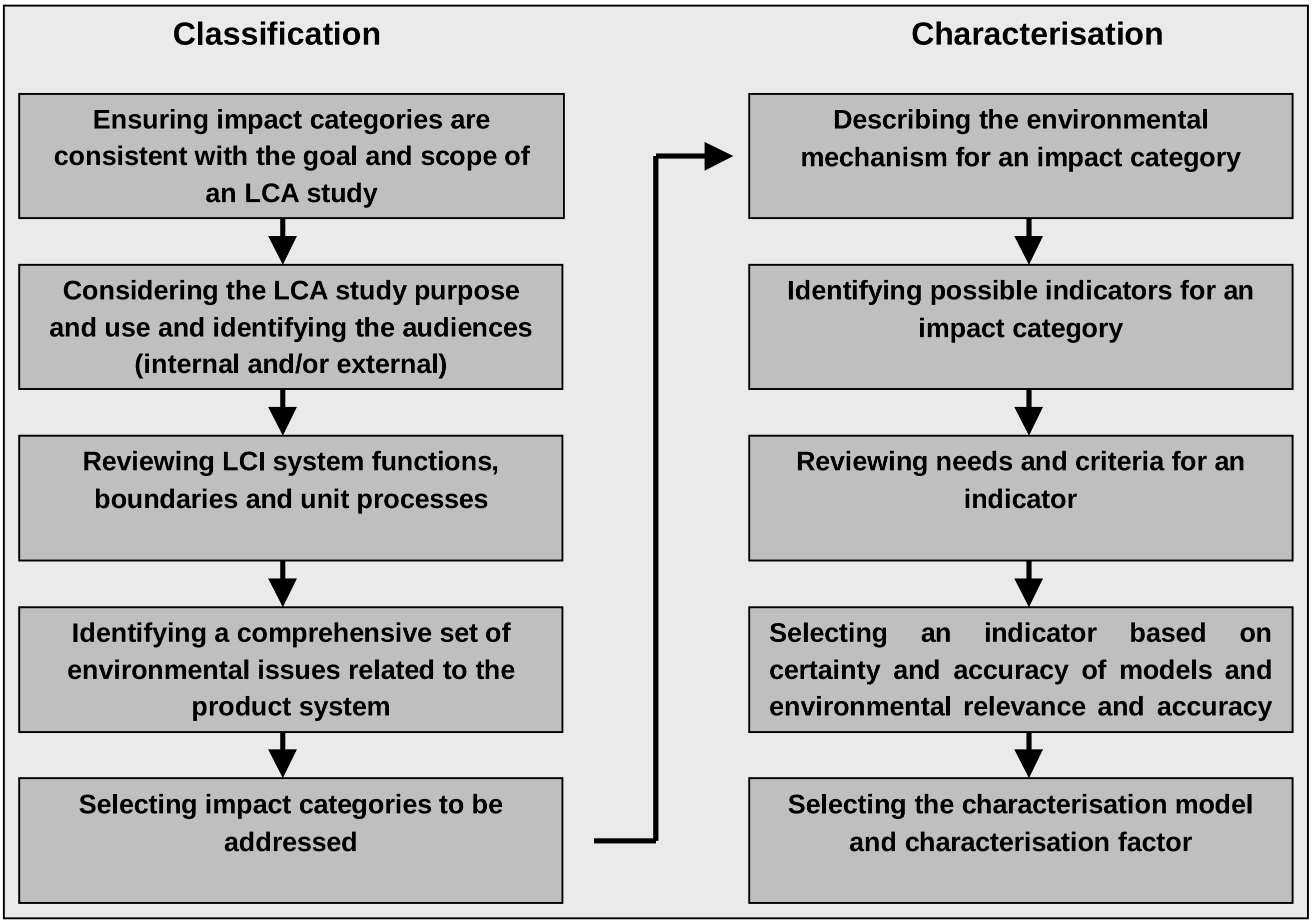
Although the approaches of the LCIA methods differ to some extent, they comply with the basic requirements as set out by ISO (see Figure 1) (ISO, 1998:3). Figure 1 illustrates that all LCIA studies must include the two elements of classification and characterisation.



Source: ISO, 2000:3

Figure 1: LCIA according to ISO 14042

The ISO 14042 standard stipulates the considerations that need to be taken into account when executing these two obligatory elements (see Figure 2). The chosen impact categories differ between the published methods, but a list of possible categories is provided in Table 2 (Lindfors *et al.*, 1995:20), some of which are used in the different methods.



Source: ISO, 2000:3

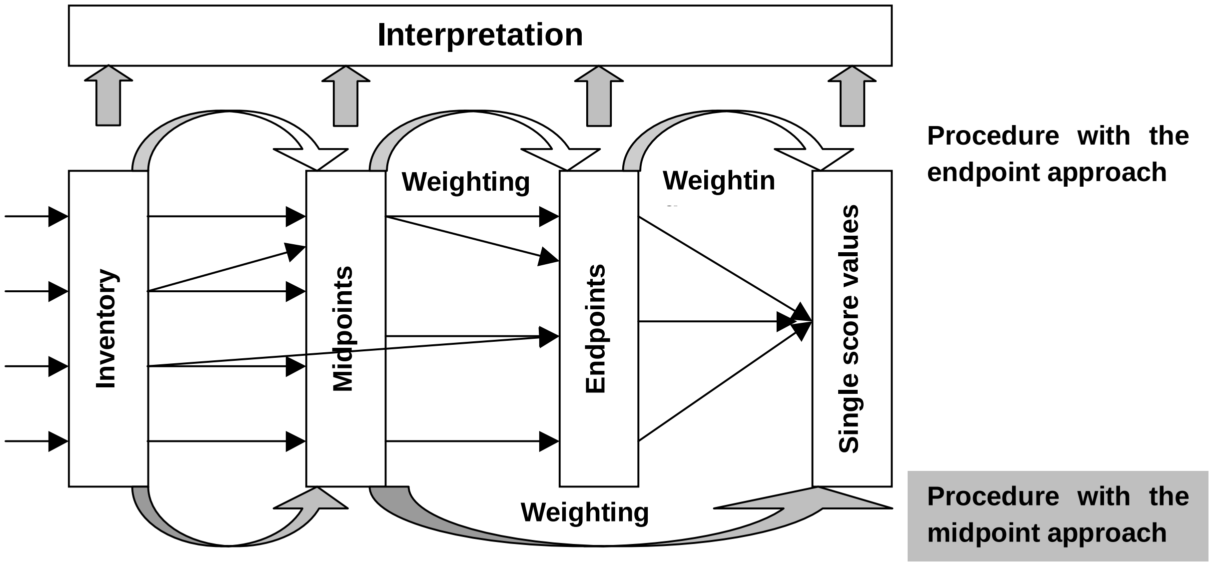
Figure 2: Schematic diagram of the steps of classification and characterisation

In terms of the optional elements of an LCIA, normalisation is usually incorporated into the methods in order to compare the impacts of a system on the different categories (Brent and Hietkamp, 2003:27). Normalisation typically considers the current environmental burden of society on the classified impact categories, e.g. an estimate of the total release of global warming gases into the atmosphere. In some of the LCIA methods a single scoring mechanism is also an option (UNEP *Industry and Environment,* 1999). A single scoring mechanism requires the LCIA method to include a weighting procedure, as shown in Figure 3 (Bare *et al,* 2000: 320). In the figure, midpoints refer to the sub-impact categories of Table 2, while endpoints refer to the first column of the table.

Main impact category (endpoints)	**Sub-impact category (midpoints)**
Resources	Energy and materials usage (can be subdivided) Water usage Land usage (including wetlands)
Human health	Toxicological impacts (excluding work environment) Non-toxicological impacts (excluding work environment) Impacts in the work environment
Ecological consequences	Global warming Depletion of stratospheric ozone Acidification of air, water and land Eutrophication of water resources Salinisation of water resources Photo-oxidant formation Ecotoxicological impacts Habitat alterations and impacts on biodiversity
Others	Inflows, which are not traced back to the biosphere Outflows, which are not followed back to the biosphere (theses are not actual impact categories, but should be included in the study)

Source: Lindfors et al, 1995:20

Table 2: List of proposed environmental impact categories for LCIAs



Source: Bare et al, 2000:320

Figure 3: Midpoint and endpoint approach for a single-scoring mechanism

The LCIA procedures are typically quantitative in nature, although qualitative approaches have also been proposed (Graedel, 1998:45). As an example, the characterisation and normalisation procedures of the CML methodology are shown in Table 3 (Guinee *et al.,* 2001:49). The results of the LCI analysis, i.e. input and output constituents, are grouped into the classified categories and a characterisation value is assigned for each constituent. The CML method is a problem-oriented approach as opposed to other methods, e.g. Eco-indicator 99 (Goedkoop *et al*., 1990:1) and EPS (Steen *et al.,* 1999), which are damage mage-oriented approaches, i.e. inventory constituents are characterised in terms of the endpoint effects on human health (e.g. Disability Adjusted Life Years), ecosystem quality (e.g. Percentage Affected Fraction and Percentage Disappeared Fraction), etc.

Impact categories	Units of measurement	Normalisation and weighting
Eutrophication	kg of PO_4^{3-} equivalence of substances	Normalisation Choice of normalised values given for: • World population (1990) • The Netherlands (1997) • Western Europe (1995) Weighting No weighting procedure included or recommended.
Ozone depletion	kg of CFC-11 equivalence of substances	
Eco-toxicity	kg of 1, 4-dichlorobenzene equivalence	
Greenhouse gases	kg of CO_2 equivalence of substances	
Acidification	kg of SO_2 equivalence of substances	
Photochemical ozone creation	kg of C_2H_4 equivalence of substances	
Human toxicity	kg of 1, 4-dichlorobenzene equivalence	
Energy use	MJ or kg of fuel per MJ	
Solid waste	kg of waste	
Abiotic resource depletion	kg of Sb equivalence	
Land use	m^2.yr (increase of land competition)	

Source: Guinee et al, 2001

Table 3: Characteristics of the CML LCIA methodology

1.2.2.1.2 Experienced shortcomings of available LCIA methods in South Africa

For certain manufactured products, the LCA results from the different LCIA methods are reasonably consistent (Sevitz *et al.,* 2003:72). However, the five European methods that are most commonly used have shown certain problems within the South African context (Brent, 2002:27):

- Certain impact categories, which are critical from a South African environmental perspective, are often omitted in the classification step, e.g. water and land availability.
- The modelling procedures for characterisation factors may not be appropriate for South Africa, e.g. the chemical transformation, and pathway and exposure scenarios for air, water and soil pollutants are most probably dissimilar in South Africa compared to Europe.
- The normalisation factors are typically not applicable to South Africa, i.e. the normalisation values do not reflect the current state of the impact categories with the South African natural environment as a reference system.
- The subjective weighting mechanisms and values are not a good indication of the importance that the South African society places on different environmental categories.

An LCIA framework and calculation procedure has subsequently been introduced in the South African context (Brent, 2003:118), whereby decision makers can evaluate impacts on four ambient resource groups that are important from a South African perspective: water, air, land and mined abiotic resources.

1.2.2.1.3 The introduced South African LCIA procedure

The framework of the South African LCIA procedure for South Africa incorporates and adheres to the requirements for a coherent set of classified environmental categories that have been proposed (Chevalier, 1999 as cited in Brent, 2003:117):

- Exhaustive (completeness): all relevant criteria for the evaluation of manufacturing systems must be included. If a criterion were excluded, the framework would be redundant in theory, although an exhaustive set of criteria may not be practical.
- Cohesion: a singular criterion can determine the preference of a life cycle system or phase of a system.

The environmental categories of the CML methodology are taken with the inclusion of water use as an additional category, and with a modification to the land use characterisation mechanism. The CML procedure has shown the least limitations in the South African context (Brent and Hietkamp, 2003:35),

and is also the most up-to-date in the public domain (as at the end of 2002) (Guinee et al., 2001).
The categories that are considered in the framework are shown in Figure 4. However, the exhaustiveness of the categories should be taken into account on a case-by-case basis. The figure also provides examples of LCI constituents that may be included in the characterisation step of the LCIA procedure, i.e. equivalency factors. As a first approximate, the characterisation factors stipulated in the CML documentation (Guinee et al, 2001) is taken for these constituents (except for land and water use), although certain limitations can be expected in the South African context (Brent and Hietkamp, 2003: 35).

1.2.2.3.1 Land and water usage characterisation

A comprehensive land cover database has been compiled for South Africa (CSIR, ARC and DEAT, 2002), which defines 31 classes of land use and natural cover. Furthermore, the total areas of the South African vegetation types that are conserved in a natural pristine state of biodiversity have been documented (Low and Rebelo, 1998). The land cover classes and conservation areas have been grouped into six main classes to simplify the use of the LCIA land use category (Brent, 2003:118):

- Natural: near-pristine conserved areas (as a percentage of the total region area).
- Near-natural: areas that resemble the natural state, although not formally conserved.
- Intensively cultivated: areas that are used for agricultural purposes.
- Moderately urbanised: residential areas on smallholdings, typically on the outskirts of cities and in rural areas.
- Extremely urbanised: densely populated, i.e. for commercial and residential use.
- Severely industrialised or degraded: areas currently used for industrial activities, or degraded due to land mismanagement practices.

The characterisation factors (land quantity and quality impacts) for the land use category have been determined from the Land Use Type (LUT) degradation severities compared to naturally reserved areas, as are shown in Table 4 (Hoffman and Shwell, 2001). The severity of degradation for specific LUTs is a reflection of many factors that are associated with the LUTs, e.g. water and wind erosion, species extinction, salinisation, acidification and other types of soil pollution (Hoffman and Ashwell, 2001).

Actual characterisation or equivalency factors are not included in the present format of the LCIA framework for the water use category. Thereby, the kilolitres of water extracted from natural reserves (surface and groundwater) by a life cycle system are taken as such (Brent, 2003:118).

1.2.2.3.2 Additional considerations with the proposed LCIA framework

Caution must be taken where LCI constituents impact on more than one sub-resource group (see Figure 4), i.e. double counting (Goedkoop and Spriensma, 2000). Furthermore, the subsequent optional valuation steps of the LCIA (see Figure 1) should be modified to indicate the extent of impacts on the four main resource groups (also shown in Figure 4) from a South African perspective. These considerations are addressed in the calculation of Resource Impact Indicators (RIIs) of an evaluated system on the four ambient environmental resource groups.

Land Use Type (LUT)	**Land degradation severity value**[a]	**Comments**
Natural	1	As a benchmark, natural rates of erosion of between 0.02 and 0.75 tonnes per hectare
Near-natural	1.75	Average taken for non-commercial croplands and veld grazing in South Africa
Intensively cultivated	1.3	Average taken for commercial croplands and veld grazing
Moderately urbanised	1.8	Average value for communal districts of South Africa
Extremely urbanised	0.9	Average value for commercial districts of South Africa
Severely degraded	2.0	Maximum documented degradation severity for South Africa (KwaZulu-Natal)

[a] Occupation: m^2.a naturally degraded
Transformation: m^2 change in natural degradation

Source: Brent, 2003:118

Table 4: Applied Land Use Type (LUT) degradation severity

1.2.2.3.3 The RII calculation procedure using the South African LCIA framework

RIIs has been introduced to evaluate the impacts of LCI constituents on the four resource groups (Brent, 2003:118). The calculation of these indicators is based on the LCIA phases of the ISO 14042 standard (ISO, 1998:7). The RII value assigned to a resource group follows the precautionary principle (Sampson, 2001). Thereby, the impact pathway of an LCI constituent (see Figure 4) that contributes to an RII value for any of the resource groups to which it contributes, is taken into account. Furthermore, the summation of the LCI contributions for a resource group is assigned as the RII for that resource group. The RII values are calculated according to the following general equation:

$$RII_G = \sum_C \sum_X Q_X \cdot C_C \cdot N_C \cdot S_C \qquad \mathbf{1}$$

Where: RII_G = RII calculated for a main resource group through the summation of all impact pathways of LCI constituents on the resource group

Q_X = Quantity of LCI constituent X released to or abstracted from a resource group

C_C = Characterisation factor for an impact category C (of constituent X) within the pathway

$N_C = (T_S)^{-1}$ = Normalisation factor for the impact category based on the ambient environmental quantity and quality objectives, i.e. the inverse of the ambient target state of the impact category

and: $S_C = \frac{C_S}{T_S}$ = Significance (or relative importance) of the impact category based on the distance-to-target method, i.e. current ambient state (C_S) divided by the target ambient state (T_S)

The application of ambient environmental quality or target objectives is therefore used, which have been proposed before as a possible alternative normalisation procedure in LCIAs (Erlandsson and Lindfors, 2003:67). The significance factor determines the relative weights when grouping the classified impact categories into the respective resource groups (see Figure 4).

1.2.2.3.4 The current and target ambient states for the RII calculation

The current (C_S) and target (T_S) states of Equation 1 have been determined for four separate regions, termed SALCA regions (see Figure 5) (Brent, 2002:119). The SALCA regions more accurately signify the region-specific water and land impacts associated with the South African manufacturing sector, without being too site-specific as is required by, for example, an EIA. The SALCA regions have been defined through the grouping of the 22 primary water catchments, which portray the surface runoff characteristics of South Africa, into areas that maximise the inclusion of the 18 eco-regions that are described in terms of information extracted from morphological and vegetation information (Kruger, 1996), and therefore also optimally represent the 68 vegetation types found in South Africa (Low and Rebelo, 1998).

The current and target ambient state values for the SALCA regions in terms of the classified impact categories of Figure 4 are currently based on the following assumptions, calculations and available ambient environmental sciences data (as at the beginning of 2002)(Brent, 2003:119):

- Current and target water quantities have been determined from available and projected annual water balances (based on assured surface and groundwater yields, human and ecosystem consumption, the transfer of water reserves, etc.) in the stipulated SALCA regions (DEAT, 2000)

- Water quality parameters are those concentrations measured at a national level in the different regions (CSIR, 2002) and for which minimum values are specified in terms of water quality guidelines for aquatic ecosystem availability or domestic use, i.e. for the protection of ecosystem quality and human health (DWAF, 1996). For the conversion of concentration values to ambient mass levels, the available and projected annual water balance volumes have been utilised.

- Regional air quality parameters are those concentrations recorded and reported on an annual basis in the vicinity of industrial activities and metropolitan areas (McClintock, 2000). Target values have again been defined from concentration values specified as an annual average for the protection of ecosystem quality and human health (Rogers and Brent, 2001). Mass values have been calculated from an assumed height of mixing above industrial and metropolitan areas in the SALCA regions.
- For global air contributions, current measurements and international target concentrations (UNFCCC, 2002) have been taken into account. These values are assumed equal for all the SALCA regions.
- Land quantity (occupied and transformed) values incorporate the current areas of all vegetation types in South Africa that are conserved in a pristine state of biodiversity (or a natural severity of degradation) (CSIR, ARC and DEAT, 2002), and the international objective of 10% naturally conserved for all vegetation types.
- Land quality is already considered in the severity of degradation of land occupation or transformation (Brentrup *et al.,* 2002:342). Although the severity of degradation is a reflection of many factors, additional ambient measured and target values have also been introduced for metallic soil pollutants (ARC, 2001).
- Mined abiotic resource values have been based on the current and projected (in 100 years) mineral (*Platinum Today*, 2002) and energy (coal) (DME, 2002) reserves that are extensively documented at national level for South Africa. These values are therefore not region specific.

1.2.3 The current deficiencies of LCAs in the South African context

South Africa is a semi-arid country with sporadic wet and dry periods. Its water resources are therefore vital. This has resulted in the national development of objectives with respect to the economic activities of the country, the health and the prosperity of its people, and the sustenance of natural heritage (Basson *et al.,* 1997:6) . These objectives and the importance of the water resources are incorporated to some extent in the normalisation and (significance) grouping values of the South African LCIA framework and RII calculation procedure. However, when quantifying the environmental impact of water usage in a life cycle system, two deficiencies are noted:

- Section 1.1.3.1 highlighted that the type of water reserve, albeit groundwater or surface water reserves, should be reflected in the characterisation factors of the water use category (of Figure 4), i.e. an amount of surface water extracted in a region does, most probably, not have a similar environmental impact when compared to the same amount extracted from groundwater reserves in the region.
- Water usage in an evaluated life cycle system is not associated with the environmental impacts on water resources alone. Treated water can be supplied to a separate life cycle system either by means of gravity or

> pumping, or a combination of both. The environmental impact categories associated with potable water supply systems thereby include global impacts (global warming and ozone depletion), regional impacts (photochemical ozone formation, acidification, resource depletion, etc.) and local impacts (human toxicity, land use, aquatic and terrestrial toxicities, etc.).

The latter emphasises the current inefficiency in the linkage between the LCI and LCIA phases of LCA studies in South Africa, i.e. although the beneficial supply of potable water in an environmental sustainable manner is critical in the South African context, the true overall environmental burdens associated with the water supply systems are not considered in LCAs at present.

The input flows for a water supply life cycle system are water from ambient reserves, energy consumption, land usage, chemicals and other materials. The output flows are supplied water, water effluent, co-products, airborne emissions, wastewater and other releases.

1.3 Research problem and rationale

International LCA literature indicates that little data is available pertaining to potable water production and supply, in particular with respect to the environmental burdens generated within the system. Furthermore, compared to most developed countries where the LCA procedure has been applied to water systems, i.e. Europe (Raluy *et al.,* 2005), the total environmental burdens associated with potable water supply are ill understood in the South African context due to dissimilar infrastructure associated with the limited water supply. In addition to the environmental impacts that are directly related to the infrastructure, e.g. water losses, the data of the auxiliary processes to the infrastructure is also deficient in South Africa, e.g. process-specific data of electricity generation and supply, waste management, etc. Consequently, the inaccessibility to sufficient LCI databases for South African LCA practitioners and researchers has been noted (Brent *et al.,* 2002:169). Particularly, the LCIs of the three operational parameters that are usually measured in the South African manufacturing industry (Brent and Visser, 2005:565) must be developed further: water usage, energy usage and waste produced per manufactured or supplied item.

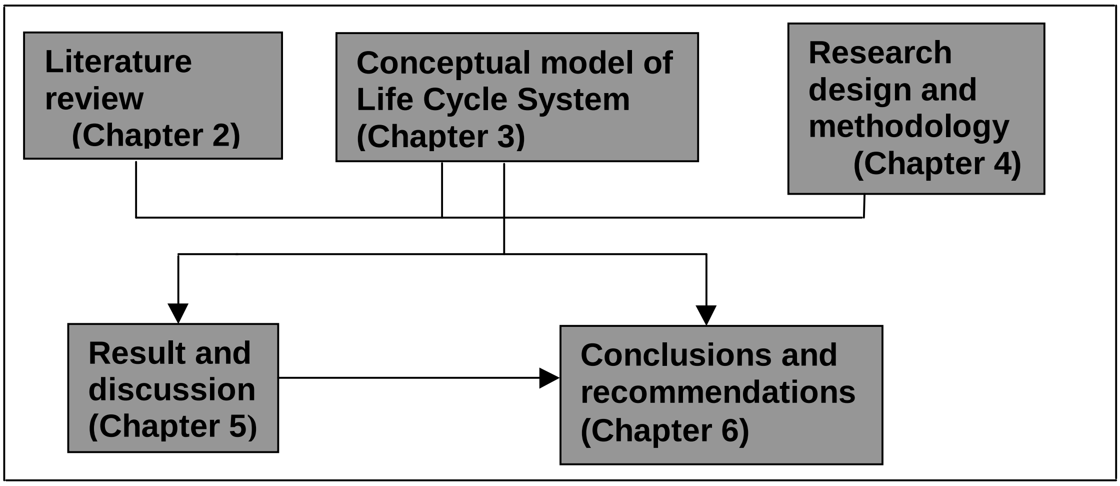
1.4 The aim of the dissertation

In general this project aims to study the environmental life cycles of potable water supply systems for industrial usage in South Africa.

A case study was used as basis in order to realise these general aims, i.e. the supply of potable water to the Rosslyn industrial zone north of Pretoria in the Tshwane metropolitan area (City of Tshwane, 2004). The Rosslyn industrial zone was chosen because the automotive manufacturing industry is rapidly expanding there (Venter, 2004), and the environmental impacts coupled to water usage have been questioned in this industrial sector (Brent and Visser, 2005:565). Within this context, the specific objectives of the dissertation are therefore:

- To compile detailed LCI data of the supply of potable water to the industrial area of Rosslyn, which includes all interacting constituents between the technosphere and nature, i.e. the extraction of resources and discharge into resources.
- To conduct an LCIA of the compiled LCI in order to ascertain the overall potential environmental burdens associated with the supply of potable water to the Rosslyn industrial area.
- To identify key environmental aspects that should be considered where water is used in the manufacturing sector in other regions of South Africa.
- To identify possible shortcomings (for further research) in the LCA tool and associated methodologies when it is applied for decision-support in the South African manufacturing industry.

1.5 Layout of the document



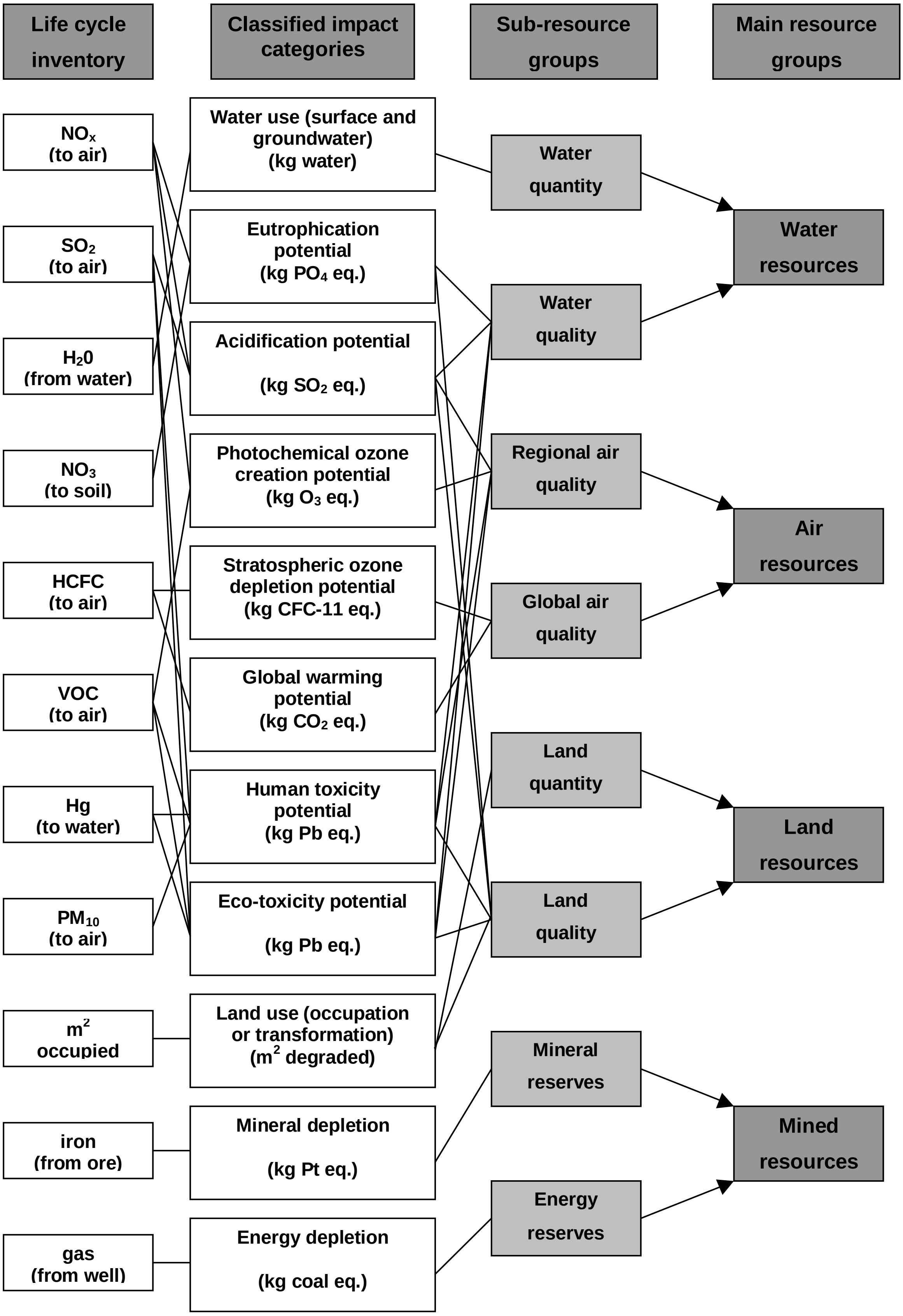
1.6 Conclusion

South Africa's water resources are limited and – in global terms – scarce. The situation is worsened by population growth and the demands of a vibrant economy, compounded by inequities in allocation, largely on racial grounds and inefficiency in use (Asmal as cited in Basson 1997:5).

The life cycle inventory data pertaining to the environmental impacts associated with the potable water supply system is still at the preliminary stage of its development in South Africa.

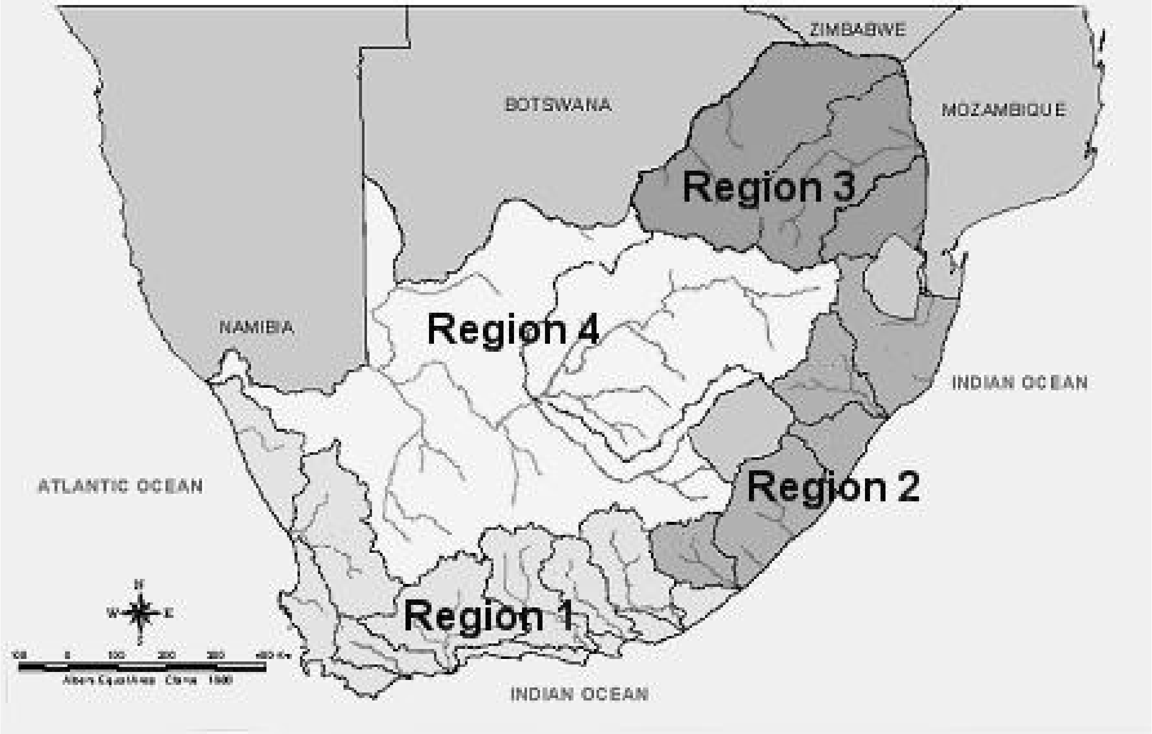
The environmental LCA as an environmental tool, which originated in the late 1990s, is used to assess and evaluate the environmental burdens associated with water use. In order to do so, the Rosslyn industrial area is used as a case study to develop this dissertation.

The dissertation aims to investigate the life cycle of the potable water supply system from the production to the end-consumer.



Source: Brent, 2003:118

Figure 4: Framework of the South African LCIA procedure



Source: Brent, 2003:119

Figure 5: SALCA regions grouped from primary water catchments

Chapter 2: Literature review

2.1 Introduction to the literature survey

The literature review has been undertaken both nationally and internationally, using the *International Journal of Life Cycle Assessment*, *Cleaner Production* and *Industrial Ecology*, as well as books and documents on the subject.

The purpose of this literature review is to avoid duplication and obtain guidance from other role players and LCA practitioners.

A number of LCAs and approaches to water use were selected and reviewed. The literature review included:

- The LCA of water resources directly extracted from nature, with special attention to the potable water supply system from the production to the end-consumer using the industrial consumption, for example in the manufacturing industry.
- How other LCA practitioners have developed their thinking in the LCA of the potable water supply system in both national and international water industries.

The literature review was concluded with a comparison of the emerged results

2.2 Current theories

This review indicates that a number of LCAs of water resources have been developed, including:

- **An LCA of water production technologies (Reverse osmosis desalination versus the Ebro river water transfer):**
  The LCA was developed to analyse and compare the environmental loads of different water production technologies in order to establish, in a global, rigorous and objective way, the less aggressive technology for the environment. Raluy *et al.* (2004) have proven that reverse osmosis is a less aggressive desalination technology for the environment. Its aggression is one order of magnitude lower than that of the thermal processes. The main contribution to the global environmental impact of reverse osmosis comes from the operation, while the other phases (construction and disposal) are almost negligible. In the case of the Ebro river water transfer, the contribution of the operation phase is also the most important one, but the construction phase has an important contribution, too.

- **LCA and life cycle costing of water tanks as a supplement to mains water supply:**
  The use of water tank installations was evaluated to determine the life cycle costs and the life cycle environmental impacts compared to conventional reticulated water supply. Hallmann et al. (2003:5) emphasise that the energy and material impacts of water tank

manufacture and operation are substantially higher, in percentage terms, than the energy in equivalent reticulated water supply systems, especially when a pump is used with the water tank. This resulted in the absolute impacts of the water tank not being large in proportion to other impacts. Avoided water storage infrastructure is not significant in the context of water tank use. It is not large enough to offset the impacts of the water tank construction and operation.

- **LCA of drinking water and rainwater for toilet flushing:**
  The LCA was used to quantify the environmental impacts of these systems and to identify factors in each system. Crettaz *et al.* (1999:2) point out that the scenario with conventional water supply systems presents a lower energy requirement and lower environmental loads than recuperation scenarios. Sensitivity analyses indicate that the recuperation is energetically favourable only when the energy required for the water supply is higher than 0.8kWh/m^3. The study reveals that low-flow toilets should be promoted, as they lead to significant reductions in energy consumption, which is advantageous for environmental solutions.

In South Africa, a great deal of research has been done on the LCA of water resources, mostly in the use of LCA for the production of potable water and in the selection of water treatment processes. The results that emerged in both studies are that the energy consumption in the operation stage of water treatment is seen as the most important stage (Friedrich and Buckley, 2002:56).

2.3 Need for new theory: LCA of water use system

LCA in South Africa is still in a developing stage of application due to a number of limitations, based on its methodological framework and use of LCA as a tool, data availability and the specific procedure to execute the EIA phase of the LCA. However, the literature searches through the Internet and material downloaded from various websites play a large role at this stage, because it allows access to some of the more recent information pertaining to the LCA methodology.

This dissertation is the first one done on LCA studies in South Africa and the first one on water use, focusing on the industrial area, particularly the manufacturing industry. There is no similar study comparable locally and regionally in terms of the result. It was, therefore, proposed to compile a comprehensive LCI data of water use as a direct extraction from nature. Nevertheless, the comparison between the few studies developed in LCA, as mentioned above, is limited due to different objectives and due to the fact that different systems were investigated. In spite of these differences, a similar result emerged: the energy consumption or the electricity usage in the water treatment unit processes was identified as one of the major environmental burdens that lead to toxicity potential category. This is in accordance with the current study.

2.4 Conclusion

From the literature review, the main aspect was more about the technologies of potable water production. The LCA was done to compare and evaluate the environmental loads associated with each technology used separately.

In the LCA of water use from tanks, LCA, as an environmental tool, was used to evaluate the cost and environmental impacts in order to make a comparison with the conventional water supply system. The life cycle assessment was used to evaluate the environmental loads and energy requirement of drinking water and rainwater for toilet flushing. According to this survey, there is still a need to develop the LCA pertaining to the potable water use as a direct extraction from nature.

Chapter 3: Conceptual model: The water supply life cycle system to Rosslyn

3.1 Introduction to the life cycle system of water supply to Rosslyn

The life cycle that was studied is the supply of potable water to the Rosslyn industrial zone by Rand Water (Rand Water, 2004).

At this stage, the model for the life cycle system procedure should incorporate and adhere to the requirement, i.e. from raw water extraction to water works and finally supplied to the end-consumer, which is the Rosslyn industrial zone, in order to evaluate the environmental loads associated with each stage of the system.

3.2 The potable water supply system

The main unit processes that are included in the supply system are summarised in the schematic diagram of Figure 6.

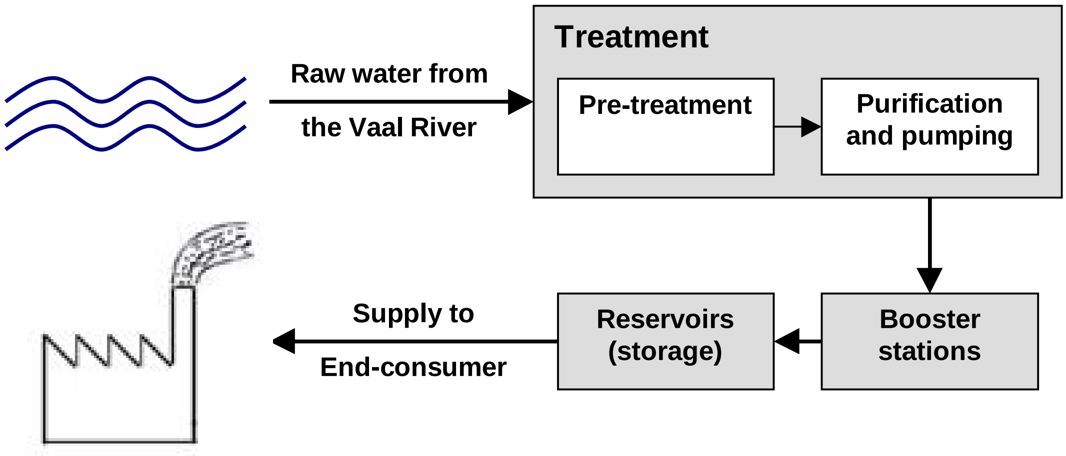


Figure 6: The water supply system for the Rosslyn industrial zone

3.2.1 Overview of the operation of the water supply system

Untreated water from the Vaal River enters the water works at the Zuikerbosch purification facilities and primary pumping stations. The stations are Zuikerbosch numbers 1, 2, 3, 4 and 4b. The treated water is then boosted to secondary pumping stations. With respect to the treated water that is finally supplied to the Rosslyn industrial zone, this is the Palmiet (approximately 46 km) booster at an altitude of roughly 1 435 m above sea level. The potable water is then pumped through pipelines to the Klipriviersberg group of reservoirs and storage tanks at the highest level of 1 795 m above sea level. Figure 7 illustrates the Rand Water network from the Vaal River to the different reservoirs. At the reservoirs the pressure is broken and water is gravitated, i.e. no power is used, to Rosslyn, which consumes in the region of 7 megalitres per day at an altitude of 1 260 m above sea level.

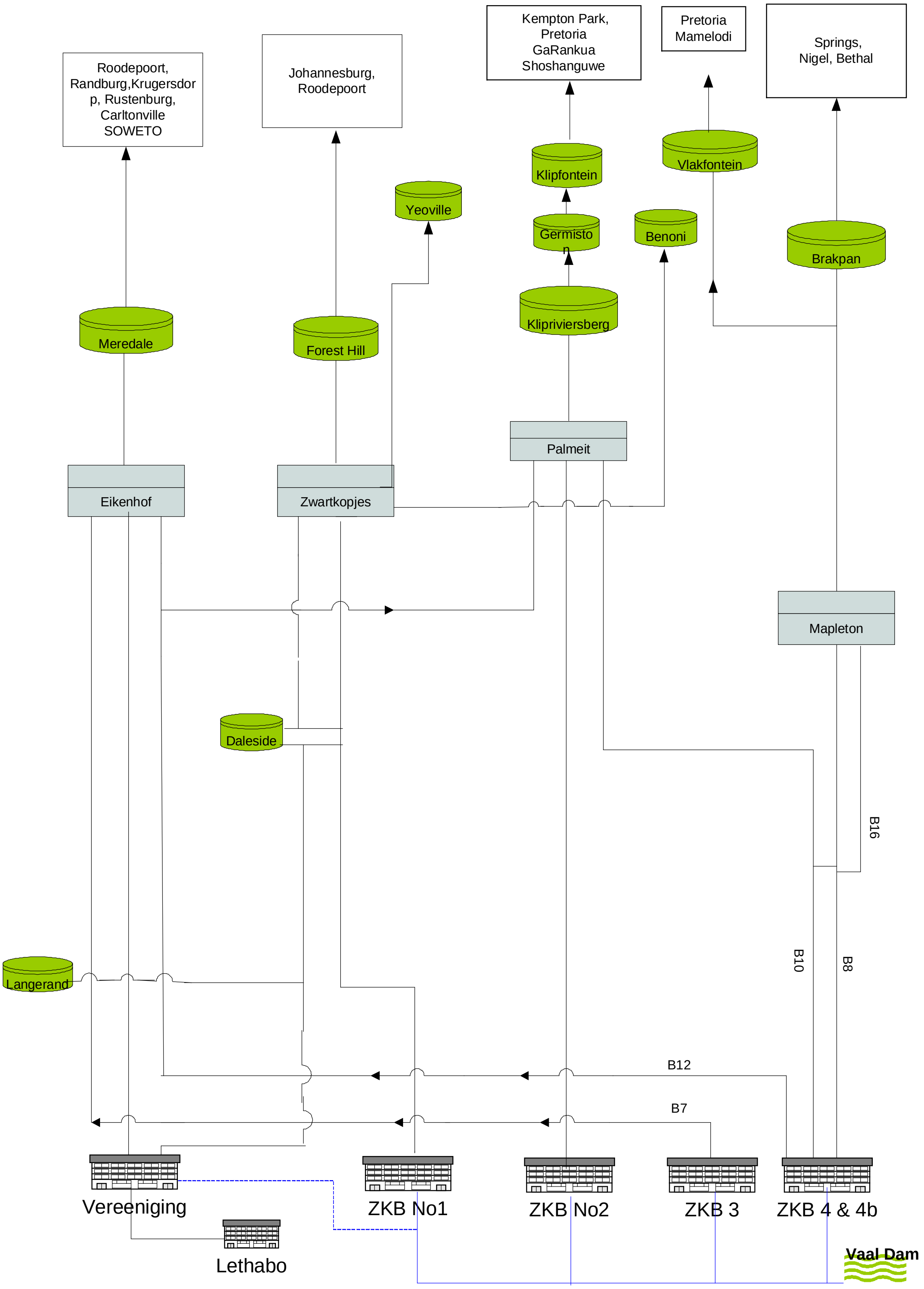


Figure 7: The Rand Water water-supply network from the Vaal Dam

3.2.2 Water purification process at Zuikerbosch

Rand Water extracts raw water from the Vaal Dam via a canal and a gravity pipeline, and pumps raw water from the Vaal River barrage reservoirs at Lethabo, Zuikerbosch and Vereeniging. The raw water passes through metal bars or screens, which trap large water plants, water animals, etc. The water from the Vaal Dam contains highly dispersed particles, which, because they are colloidal, tend to remain suspended for a long period. Conventional treatment processes then remove the suspended material and disinfect the water. The purification process involves seven stages: coagulation, flocculation, sedimentation, carbonation and stabilisation, filtration, and chlorination and disinfection (Rand Water, 2004).

In summary, limestone (calcium carbonate) is fired at 1 200ºC in a shift kiln at the Zwartkopjes facility to convert it to calcium oxide and CO_2 off gas. The burnt limestone is crushed and slaked with water in rotating slakers to produce slaked lime or calcium hydroxide. The slaked lime is then added to the water as the main coagulant to destabilise the electrostatic charges of the suspended particles in the water. A further chemical, activated sodium silicate (floc) is added to assist the process. Passing the water over weirs enhances the mixing of water and chemicals (Friedrich and Buckley, 2002:15). The water, together with the floc, flows slowly through a large sedimentation tank and the floc settles out by gravitation to form sludge.

The sludge from the sedimentation tank is pumped approximately 2.5 km to Panfontein sludge disposal site. The water flows into carbonation bays where the pH, which is approximately 10.5 after the coagulation and flocculation processes, is lowered (to between 8.0 and 8.4) by bubbling CO_2 through the water. Thereafter, the water passes into the filter houses where it flows through gravity sand filter beds of finely graded silica sand and pebbles. It is then chlorinated (with chlorine gas) in order to kill germs before it is distributed to the consumers. An illustration of the overall process is shown in Figure 8.

Water Purification System

	A. Vaal Dam	B. After sedim.	C. After carbonation	D. After filtration	E. Consumer
Turbidity (NTU)	75-240	5-10	5-10	0.41-0.84	0.41-0.84
Alkalinity (mg/l as CaCO3)	42-65	70-120	70-120	70-115	69-115
pH	7.5-8.2	10.6-11.1	8.0-8.4	8.0-8.4	7.9-8.3
Conductivity (mS/m)	12-17	18-28	18-28	18- 28	18-28

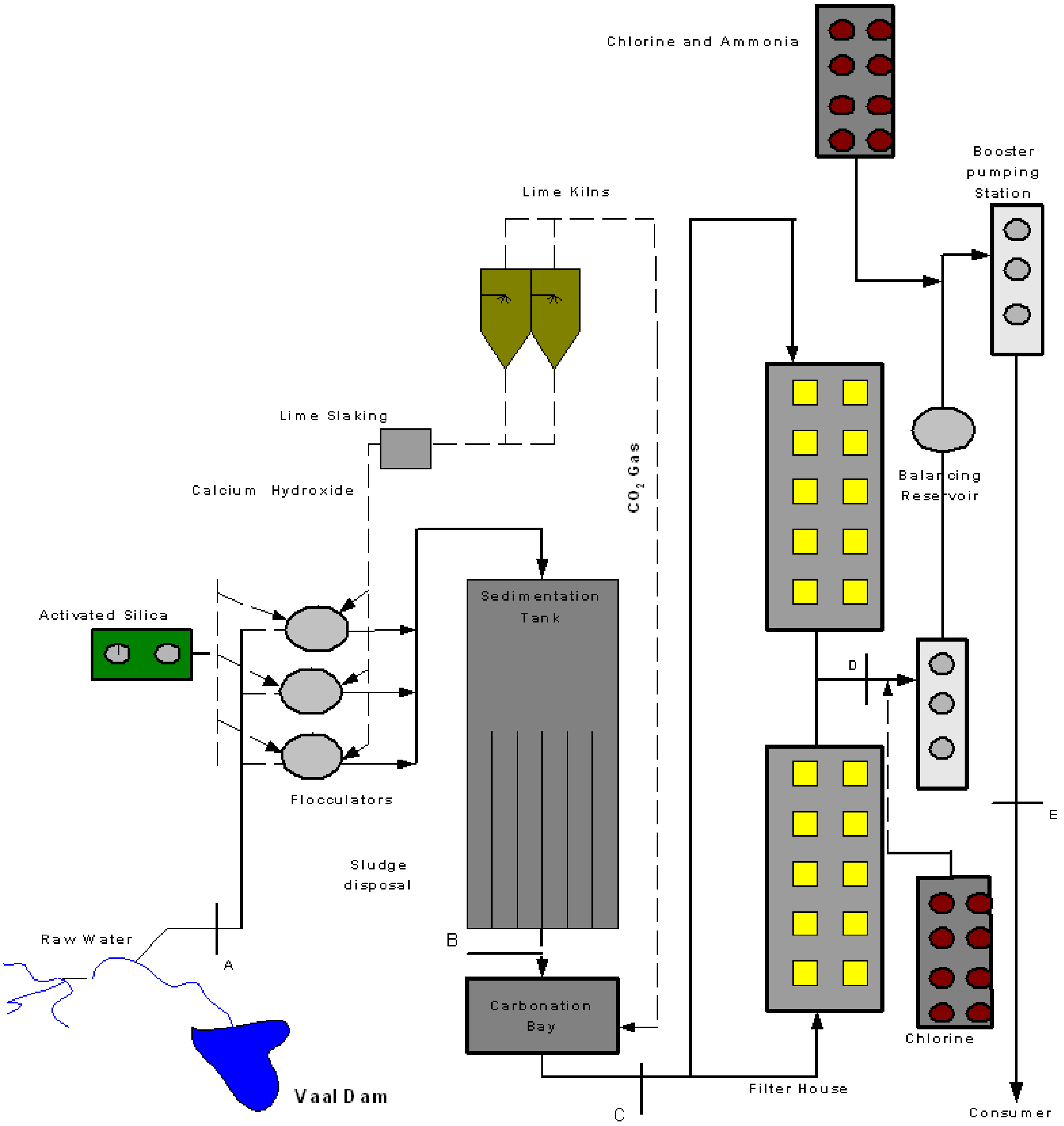
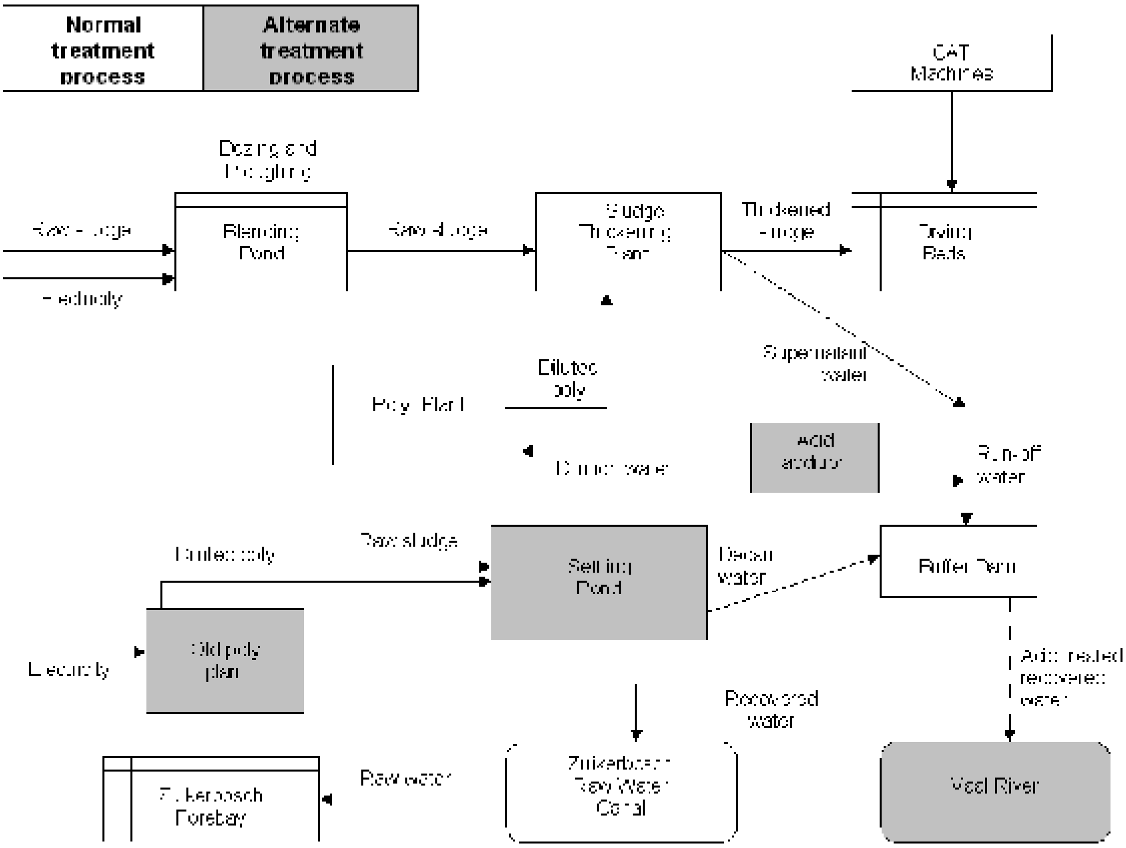


Fig 8. The water purification system at Zuikerbosch

3.2.3 Panfontein sludge disposal site

The sludge generated in the purification of raw water at the Zuikerbosch purification facility is treated at the Panfontein sludge disposal site. The site processes between 300 and 1 300 tonnes of dry sludge a day in 280 hectare drying beds. Figure 9 illustrates the process flow diagram of the sophisticated and automated sludge treatment and disposal.

Figure 9: Panfontein sludge treatment and disposal process



The raw sludge is stored in a balancing pond where mechanical agitation keeps the solids in suspension. The balancing pond serves to condition the sludge, and acts as a holding pond from which the sludge is pumped for processing. Thereafter, dewatering of the raw sludge occurs by means of high rate sludge gravity thickeners. In this process, an anionic polyelectrolyte flocculent is added to the raw sludge. Flocculation occurs and the aggregation of the solids causes a phase separation within the (now treated) sludge. These solid particles settle at the base of the thickeners, where mechanical moving rakes scrape the thickened sludge to the centre. Underflow pumps extract this product (now at a consistency of 18-20% m/v) from the thickener for dispersion onto the sludge airdry paddocks in cycles, where it is left to dry. Clear supernatant water recovered during this treatment process can be as high as 90-95% of the raw sludge volume, and is recycled to Zuikerbosch for reprocessing with the raw water (Rand Water, 2004). The dewatered sludge is landfilled in a municipal landfill under the permit conditions prescribed by the DWAF.

3.2.4 Auxiliary processes

In addition to the main and sub-unit processes that are required in the direct value chain of the supplied water, auxiliary processes are required. These are, but are not limited to, the following:

- Energy inputs, in the form of electricity and fuel, which must be generated or produced separately with associated environmental impacts and raw energy materials, e.g. coal that may be required for boilers, etc.
- The manufacture of chemical materials that may be required in the life cycle system, e.g. chlorine gas for the chlorination phase of the purification step.
- Specific energy and material requirements during abnormal operations, e.g. when maintenance on any unit process is required.
- Construction material for the capital equipment in the life cycle system.
- Transportation within or between unit processes, e.g. rail or road transport of required materials, piping of the supplied water, etc.

Therefore, by considering all the important unit processes, the overall environmental burdens coupled to the life cycle system may be calculated.

Chapter 4: Research design and Methodology

This chapter contains the methodology followed in the dissertation in order to conduct the LCA as given in the conceptual model formulated above. The general methodology used in this study starts from the proposed model of the water supply system in which the ISO standards procedural framework is applied.

4.1 Approaches to the Research Methodology

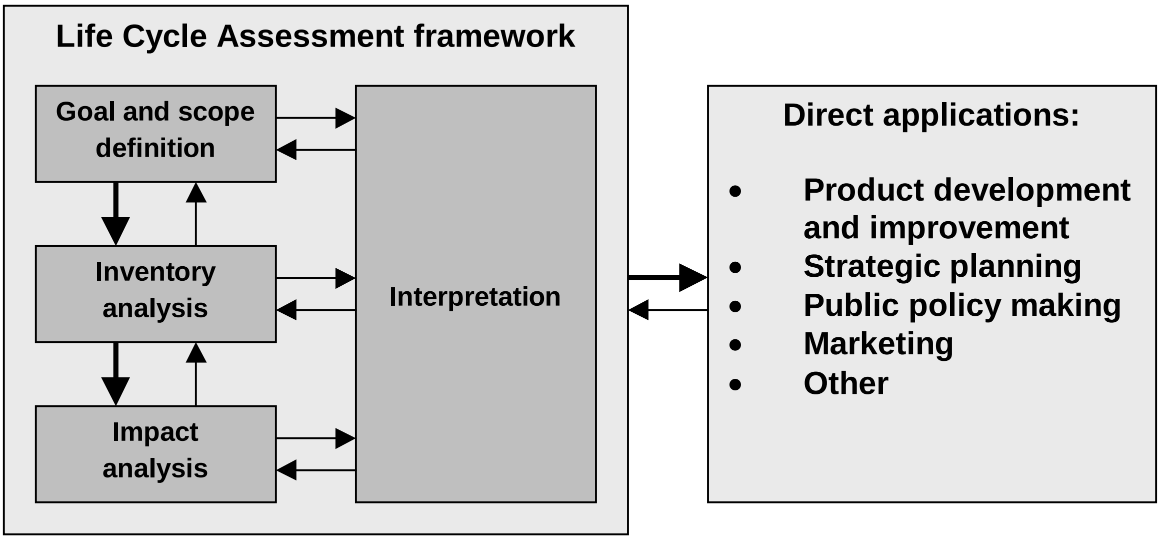
The dissertation aims to conduct an LCA of water use in the industrial area and to identify the environmental loads associated with the system. The environmental loads comprise all extractions of available resources and effluent into the environment that take place during the life cycle system of water use. The conceptual model includes the set of unit processes involved in the production, supply and use of potable water up to the end-consumer. The route that leads to the Rosslyn industrial area in terms of the water supply system from the Vaal dam, the point of extraction, to Zuikerbosch were taken into consideration. By means of the data collection, the model generates the complete life cycle system, the starting point of the data collection stage. The data information sheet was then designed to collect data at each stage of the system under study.

4.2 The Research Strategy

Having created the water supply system diagram (Figure 6), data was collected, processed and analysed in order to gain insight into the critical unit processes (sub-systems) that give an indication of potential impacts on the environment.

This dissertation closely followed the four phases as stipulated in the international standard for conducting LCAs (ISO, 1998:4), which have been described in Section 1.1 and illustrated in Figure 10:

- Goal and Scope definition
- LCI analysis
- LCIA
- Interpretation, conclusions and recommendations



Source: ISO, 1997:4

Figure 10: Standardised phases of the LCA procedure

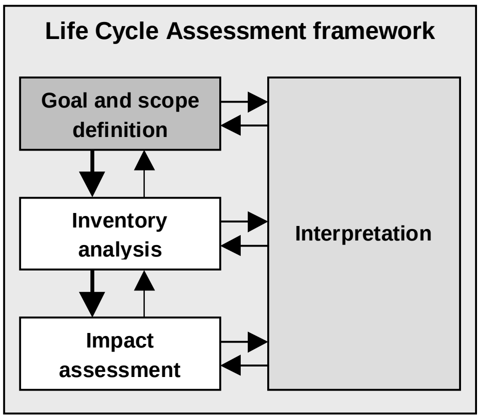
For the calculation procedures, where data was not available, intrinsic calculations were carried out based on literature and qualitative methods. The data gathered at this stage gave a reasonable coverage of the potable water supply system from the extraction to the end-consumer.

The methodology used for the impact assessment phase was the proposed framework for a South African LCIA procedure developed in South Africa. The inventory analysis conforming to the scope of this dissertation provides overall inventory of energy and other resources requirements, effluent and emissions, dust fallouts and solid or liquid wastes for the system under study.

General comments and recommendations, based on the LCA experience of this study, are made in the final chapter, Chapter 6, which also contains recommendations for further research.

4.3 The research methodology

4.3.1 The goal and scope of the study



Defining the goal and scope is the most important phase of an LCA as it lays the foundation for the study. This step fixes the objectives of the LCA, determines the potential applications of the LCA study; and assesses what it can and cannot be used for (Wenzel *et al.,* 1997). Figure 10 illustrates the LCA framework including the goal and scope of the study.

4.3.1.1 The goal of this LCA study

The goal of an LCA states the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated (ISO, 1998:5).

The primary reason for conducting this study was to obtain environmental data about the life cycle of supply systems of potable water for industrial use in South Africa. Possible improvements in the environmental performance of such systems could then be identified. Specifically, an LCA was conducted to establish the potential environmental impacts associated with water use in the Rosslyn industrial zone north of Pretoria in the Tshwane metropolitan area (City of Tshwane, 2004).

The audiences or target groups of this LCA study are:

- LCA practitioners and industry consultants; the generated LCI data can be useful for future LCA studies in South Africa and the study demonstrates the extent of environmental impacts associated with such a water supply life cycle system.
- Research in environmental sciences disciplines and the field of LCA; shortcomings in the current LCIA methodology may be identified and future research possibilities identified.
- Decision makers that use LCA results, e.g. environmental authorities and planners at national, provincial, local and operational level, and engineers involved in waterworks.

4.3.1.2 The scope of this LCA study

The scope is determined by the objectives of the LCA. The ISO standard (ISO, 1998:5) recommends that the following items are considered and clearly defined:

- The system under study with its functions.
- The specific functional unit to which all environmental impacts relate.
- The boundaries of the system.
- The allocation of inventory constituents and environmental impacts between different life cycle systems.
- The type of impact assessment methodology followed in the study.
- The data (quality) requirements for the study.
- The assumptions of the study.
- The limitations of the study.
- The type of critical review for the study.
- The type and format of the report required for the study.

4.3.1.2.1 The system under study

The system under study is the supply of potable water to the Rosslyn industrial zone by Rand Water. The system has been described in Chapter 3 and shown in Figure 6, which illustrates the water supply system model for Rosslyn. The system starts at the Vaal Dam where raw water is extracted to be treated and purified at the Zuikerbosch plant. Thereafter it is boosted and pumped to the end-consumer.

4.3.1.2.2 The functional unit of this LCA study

The functional unit is 1 megalitre per day of potable water supplied at Rosslyn at the quality stipulated in Rand Water guidelines and suitable for industrial use, e.g. in a brewery. All inventory effluent is reported for this functional unit. Furthermore, the overall environmental impacts, calculated from the inventory, are presented referring to the functional unit.

4.3.1.2.3 The boundaries of the water supply life cycle system

According to the ISO 14040(1998) documentation, the system boundaries determine which unit processes shall be considered in the LCA study. The unit processes that serve to provide input streams into the life cycle system, and which are included in the boundaries of the study, were determined by the relative mass, energy and economic value of the input streams compared to the functional unit (Raynolds *et al.,* 2000:42). According to this Relative Mass-Energy-Economic (RMEE) method, unit processes with a mass, energy and economic ratio of less than 1% compared to the functional unit will contribute less than 1% of the overall environmental impacts of the life cycle system (Raynolds *et al.,* 2000:96). The functional unit of this case study, i.e. supplied water, does not have a functional energy value in itself and this parameter was therefore not considered. It should be noted that problems have been associated with cut-off procedures in life cycle studies (Suh and Huppes, 2002:135). However, the RMEE method was assumed adequate to determine the most important processes that contribute to the impacts of the overall system. As an additional criterion, unit processes that contribute less than 1% to the impacts of all of the considered environmental categories were excluded from the LCA study.

4.3.1.2.4 Allocation procedures of this LCA study

Referring to the ISO 14040 documentation , allocation procedures are needed when dealing with systems involving multiple products. However, allocation of environmental burdens (resource consumption and effluent) to products and by-products resulting from the same industrial processes is still a debated issue in the field of LCA (Rand Water, 2004) . ISO notes that allocation should be avoided, if possible, by:

- Sub-dividing unit processes where allocation is required.
- Expanding life cycle systems to include by-products.

If allocation is unavoidable, it should be based on:

- The physical causal relationship of products and by-products.
- The economic value of products and by-products.

For this LCA study, if allocation is unavoidable, the economic value is the predominant criterion. Consideration must also be given to recycling. Where open-loop recycling occurs, i.e. products and materials flow to other systems external to the water supply system, the environmental burdens associated with the use of the products and materials were allocated to the external system. The environmental burdens of closed-loop recycling, i.e. products and materials recycling within the water supply life cycle system, were included in the LCA study.

4.3.1.2.5 The data requirements of this LCA study

The data quality requirements should address the following (ISO 1998:6):

- Time-related coverage, i.e. the required temporal scale of the LCA study.
- Geographical coverage, i.e. the required spatial scale of the LCA study.
- Technology coverage.
- Precision, completeness and representativeness of the inventory data.
- Consistency and reproducibility of methods used throughout the LCA.
- Sources of the data and their representativeness.
- Uncertainty of the information.

The LCA study considered the supply of potable water on an annual basis with typical operations of the Rand Water network in the Gauteng Province only. The input and output inventory of the life cycle system, including monthly consumption of land, water, energy and materials, as well as discharges, were derived from onsite investigations at the present (2003 to 2004) Rand Water facilities. The data was therefore collected during technical visits to several selected plants (Panfontein, Zuikerbosch, etc.) and from annual reports. With respect to data pertaining to the reservoirs, the Tshwane municipality's database was used. Other necessary data was gathered from international literature where direct data was not obtainable or transparent and calculated to the daily statistics (e.g. losses through leaks or evaporation) of the actual production and supply system of potable water.

The precision, completeness and uncertainty of the data were tested through sensitivity analyses during the LCI and LCIA phases as part of the interpretation of the LCA study (see Chapters 4 and 5).

4.3.1.2.6 The assumptions of this LCA study

The following assumptions of the LCA study must be noted:

- At the time of conducting the LCI, it was assumed that the Rand Water network supplies all the water that is consumed in the Rosslyn industrial zone.
- Where data from literature was used, it was assumed that similar processes are used in the production and supply of potable water.
- Eskom generates the electricity that is consumed for the production and supply of potable water.
- For the life cycle system, it was assumed that the difference between the raw water inflow and supplied water outflow is the water that is lost through either effluent (leaks) or accidental releases such as spills.

4.3.1.2.7 The limitations of this LCA study

The limitations of the LCA study were as follows:

- The study focused on the Rand Water network only, and it may therefore be problematic to relate the results to other water supply systems in South Africa.
- Confidentiality issues limited the availability of certain site-specific data, or reduced the accuracy of the data with respect to true environmental performances of the different industrial processes. In terms of the latter, there is a general reluctance by South African companies to provide input data for LCA studies (Friedrich and Buckley, 2002:14). The LCI data of the electricity generation and fuel production processes, especially, are limited in the South African context. Similarly, information about chemicals that are used in water supply systems was not easily obtainable from the manufacturers due to technical and internal reasons.
- The collection of data is the most time-consuming part of an LCA and involves a great deal of time to obtain transparent and representative information about the many processes in a production system (Overcash *et al.,* 2000:153). Consequently, time constraints reduce the completeness of the LCI data.

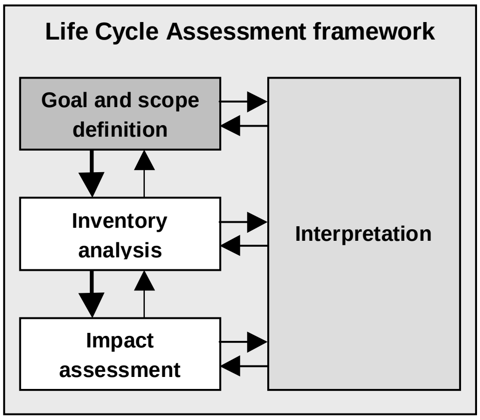
4.3.2 Life cycle inventory analysis

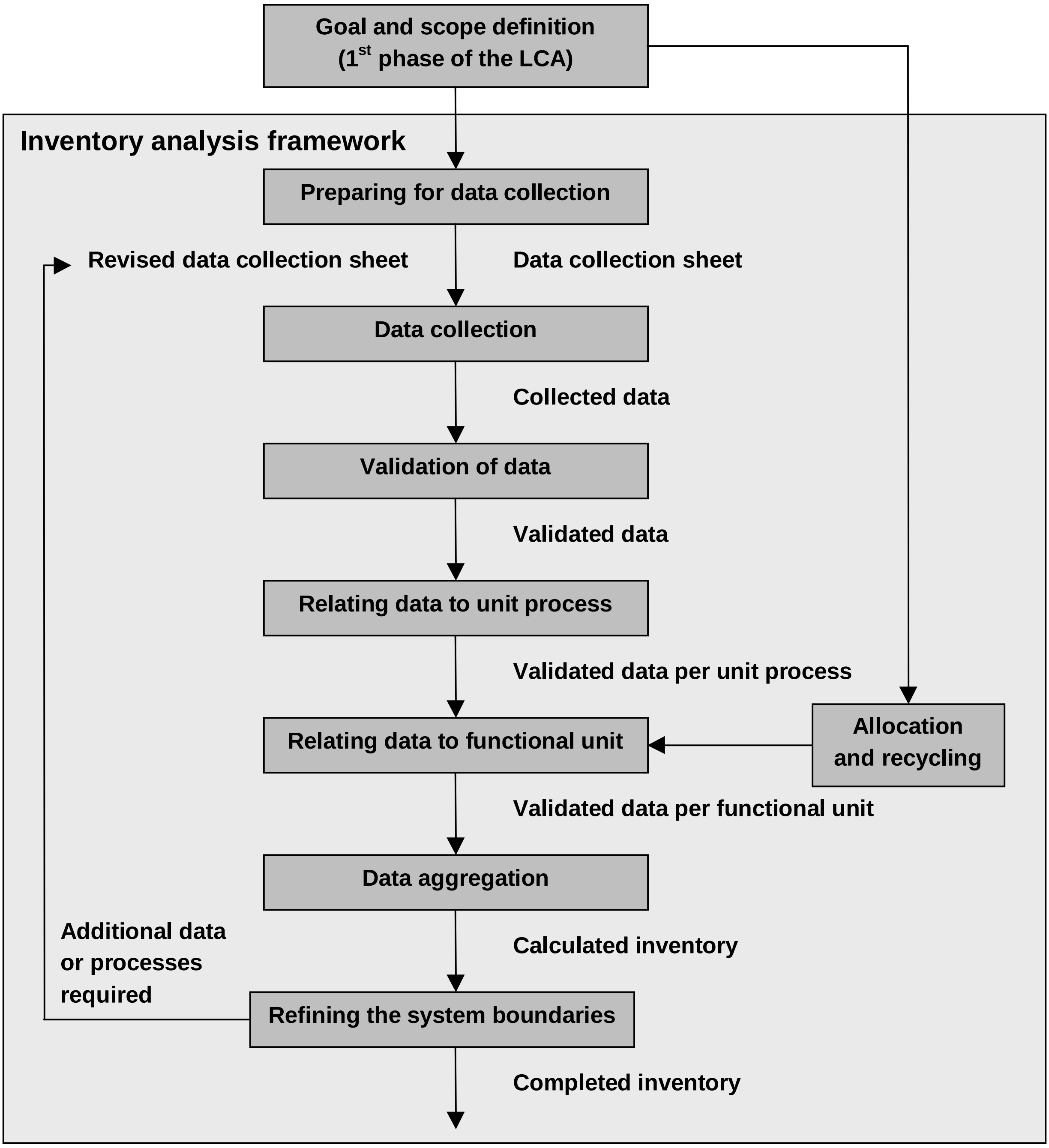
4.3.2.1 Introduction

This section provides an overview of the procedural framework for conducting the LCI analysis phase of LCA studies. Although there is broad scientific agreement on the major elements of an LCI, especially through the activities of the technical committee 207 of the International Organization for Standardization (ISO, 2004) and the UNEP/SETAC global life cycle initiative (UNEP sustainable consumption, 2004), specific procedural decisions occur at many stages in the process whilst executing LCAs. A framework for conducting the LCI analysis is well documented in the ISO publications (see Figure 11), which also define the following operational steps (ISO, 1998:8):

- Goal and scope definition that outlines the aim of the LCI.
- Preparing for data collection that defines the entire unit processes involved in the life cycle system that is assessed. This step introduces the construction of the flow diagram of the system under study and the compilation of environmental data sheets for each unit process in the life cycle system.
- Data collection that provides practical guidance on how to collect data and requires a quantitative and qualitative description of the inputs and outputs of each unit process.
- Data validation to analyse the completeness, variability and uncertainty of data.
- Relating data and data aggregation that contains intrinsic calculations for each unit process in the life cycle system, whereby quantitative input and output data are recalculated in relation to a reference flow (for each unit process) and in relation to the functional unit of the LCA study (see the Phase 1 report).
- Refining the system boundaries that outline the decisions of the inclusion or exclusion of the data in the system boundaries.

In summary, an LCI analysis is concerned with the data collection and calculation procedures to quantify inputs and outputs of a system (ISO, 1998:8). Figure 10 illustrates the LCA framework including the LCI.





Source: ISO 1998:8

Figure 11: Procedure for the inventory analysis phase of an LCA study

4.3.2.1.1 Experienced limitations of LCI available data in South Africa

South Africa, as a developing country, comprises a mixture of high-tech industries and basic, outdated technologies. The data acquisition process for the inventory analysis subsequently experienced some limitations (Brent et al., 2005:169). No significant full LCI studies have yet been performed in South Africa that is available in the public domain (Stinnes, 1995). Much of the process-specific data is not yet available and assumptions have to be made. For example, comprehensive measurements of emissions into the atmosphere are not mandatory, and effluents that are released into the municipal effluent system have in many cases not been analysed.

4.3.2.1.2 The current deficiency of LCIs of water use in South Africa

South African water resources are limited and – in global terms – scarce. The situation is worsened by population growth and the demands of a vibrant and growing economy, compounded by inequities in allocation and inefficiencies in use (Basson *et al.,* 1997:5). As a country, South Africa is approaching the full utilisation of its water resources and the gravity of this situation must be recognised. However, when performing an LCI of water use, which will emphasise the extent of the water resource problem to a certain degree, a number of deficiencies are noted:

- Water losses occur in all life cycle stages of water supply, either through evaporation or leaks, or a combination of both. This data must be reported in order for the LCI of water supply and use to be accurate.
- The input data or flows at reservoir level are limited to the amount (tonnes) of water that is pumped into the reservoirs on a regular basis. Land use and construction and/or maintenance materials and energy should be reflected in the inventory data of the storage stages in the life cycle of water use. Similarly, all input and output parameters or flows of the different stages in the water supply life cycle must be considered.
- The LCI on the extraction and potable water production processes are of primary importance to all industries involved in the supply and consumption of potable water. Municipalities and industrial areas should therefore consider this aspect and compile regular reports on water use and make such information accessible in the public domain.

4.3.2.1.3 Rationale for this LCI

As discussed in Section 1.3, the literature indicates that LCI data in the South African context is limited with regard to the supply of potable water. Information gaps are subsequently experienced in some of the life cycle stages of water supply. However, through the systematic procedures stipulated in the ISO 14041 guidelines (ISO 1998:8), the required inputs and outputs of all relevant life cycle stages can be obtained, whereby a comprehensive EIA can be performed.

4.3.2.1.4 Objective of the LCI phase in the overall LCA study

The LCI phase in this research project aimed to fulfil the following objectives:

- To establish a base line of information of the overall material and energy resource use, and environmental burdens associated with effluent, for the water supply life cycle system of the Rosslyn industrial area of the Tshwane municipality.
- To identify stages within the life cycle system where a reduction in resource and effluent might be achieved.
- To guide the development of new water supply systems towards a net reduction of resources requirements and effluent.
- To identify the inventory constituents that must be addressed in the LCIA phase of the LCA study.

In order to fulfil these objectives, the guidelines of ISO 14041(1998:8) were followed, and specifically the abovementioned operational steps of a comprehensive LCI.

4.3.2.2 Goal and scope definition of the LCI

The LCI forms the core of any LCA study and it is the most difficult and time-consuming activity in an LCA project. In an LCI analysis, the term “system” refers to a collection of operations that together perform some defined function (Vigon *et al.,* 1993: 16). The system of this LCA study is the supply of potable water from Rand Water to the Rosslyn industrial area of the Tshwane municipality (see Section 2).

The goal of this LCI was therefore to develop an LCI database of the most important constituents or parameters associated with the production and supply of potable water to the Rosslyn industrial area, and it includes a number of operations for which the LCI must be performed. The life cycle stages for which inventory constituents were compiled initially included the following (see Figure 12):

- Purification (including waste treatment) and pumping stages.
- Booster stations.
- Energy production and supply, specifically electricity.
- Reservoirs along the supply life cycle.

The scope of this work, after constructing the initial process flow diagram, mainly centres around gathering the input and output data for each unit process within the system, e.g. from data and calculations of the daily statistics (monthly report) of Rand Water (Rand Water Supply Board, 2004). The analysis is performed to determine the contribution of each unit process to the total of environmental burdens of the studied system. The improvement efforts will be focused on those processes with relatively substantial contributions to the overall environmental impact assessment results.

4.3.2.3 Preparing for data collection

The definition of the scope of an LCI analysis establishes the initial set of unit processes and associated data categories that are considered. Since data collection may span several reporting locations and published references, defined steps are helpful to ensure uniform and consistent understanding of the product system that is modelled (ISO, 1998:9). These steps include:

- Drawing specific process flow diagrams that outline all unit processes to be modelled, including interrelationships.
- Describing each unit process in detail and listing of data categories associated with each unit process.
- Developing a list that specifies the units of measurement.
- Describing data collection techniques and calculation techniques for each data category to assist personnel at the reporting locations to understand what information is needed for the LCI study.
- Providing instructions to reporting locations to document clearly any special cases, irregularities or other items associated with the data provided.

The purpose at this stage was to illustrate the nature of the information to be collected from a particular unit process accountable in the water supply system under study.

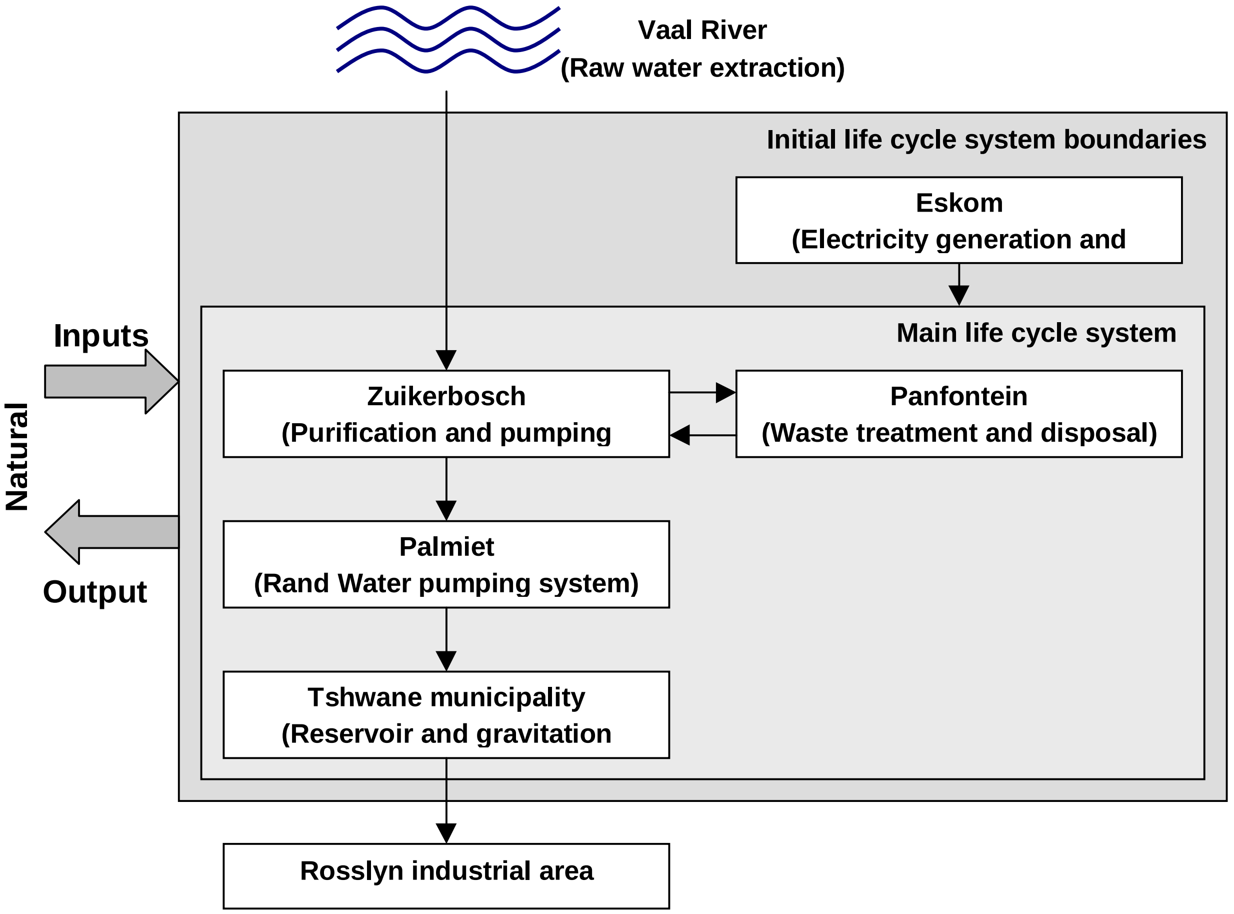


Figure 12: Simplified initial process flow diagram for the water supply system

4.3.2.3.1 Process flow diagram of the water supply life cycle system

The process flow diagram shown in Figure 12 outlines the unit processes that were included in this LCA study initially. The possible expansion of the system was dependent on the obtained data through an iterative process (see Section 3.7 below).

Environmental data sheets were subsequently constructed for the following components of the water supply life cycle system (see Appendix A):

- Water purification and pumping system (Zuikerbosch).
- Waste treatment and disposal (Panfontein).
- Rand Water pumping or booster system.
- Reservoir storage and gravitational release system (Tshwane Metropolitan Municipality).

Water use data was further obtained for the Rosslyn industrial area from the Tshwane Metropolitan Municipality. Although the Vaal River was excluded as a specific unit process, the amount of raw water supplied for treatment at Zuikerbosch was included in the environmental data sheet for the water treatment and pumping system.

4.3.2.3.2 Description of the unit processes

Considering the process flow diagram (of Figure 12), each box in the flow diagram represents a particular unit process and was viewed as a subsystem for the inventory of the water supply system as a whole. These unit processes were investigated and described individually in the overview of the operation of the water supply system (see Section 2.2.1 and the sub-sections of Section 3.4 below).

All the input and output flows were identified and the information is included in the data collection sheets (see Appendix A). Each unit process or subsystem requires inputs of water, land, materials and energy; and has outputs such as atmospheric emissions, water effluent, waste, etc. A standard inventory data worksheet was prepared to guide the data collection stage.

4.3.2.4 Data collection

The procedures that are used for data collection usually vary with each unit process in a modelled system when conducting an LCA (ISO 1998:9). In theory, each system is a collection of hundreds of thousands of unit processes (Raynolds *et al.,* 2000:38). The discharge of air, water and soil pollutants, as well as energy, material and land consumption is often deduced. In addition, due to data availability, only regulated discharges for each process are normally included in the inventory data sheet (USEPA, LCA101, 2004:15).

Input flows are the quantities of materials, land, energy or transport required for each unit process (Crettaz *et al.,* 1999:4). Input and outputs from all the processes and sub-processes are related to the functional unit (of the LCA study) and presented in the inventory data sheet.

Relevant data for this LCI analysis was mostly collected through personal interviews, as well as from literature. As far as was possible, all the data was related to 2002 figures. The potable water production data was obtained directly from Rand Water. Information on water supply after the booster stations stage was available from the Tshwane municipality. Information about the electricity production was obtained from Eskom annual reports (Eskom, 2002) and literature, together with available LCI databases (TEAM LCA, 2002).

The initial data collection therefore concentrated on the life cycle stages that were suspected to make the largest contributions to the environmental burdens of the investigated life cycle system (as shown in Figure 12). Delays were experienced at each level of data collection within Rand Water due to the workloads of the staff, and the non-familiarity of the potential benefits of the LCA study to Rand Water, e.g. the identification of losses.

4.3.2.4.1 Data collection on the purification and pumping system

The data collection commenced with the processes used at Zuikerbosch to produce and supply water. The data gathered included:

- The amount of raw water from the Vaal River.
- Materials and chemicals that are used.
- The type and the quantities of the energy inputs.
- The land use in terms of the space provided since the operation commenced.

The transportation requirements from one location to another were included in the sub-system. The transportation was quantified in terms of the distance and the mode of transport used on the site. Within each process, the energy input data was collected and converted into megajoules (MJ) of electricity to operate the process. It was time consuming to obtain the data about chemicals. Dedicated effort was needed to convince the individuals involved on the site to provide chemical information in this regard as they were not familiar with the LCA study. Where possible, the environmental releases to air, water and soil related to the various sub-processes were evaluated, quantified and included in the inventory data sheet by the type of pollutant. It should be emphasised that the water purification processes generate sludge (waste), which is handled by the waste treatment process rather than directly disposed of in the natural environment.

4.3.2.4.2 Data collection on the waste treatment and disposal

The data on sludge treatment and disposal were collected at Panfontein sludge disposal site. The data collection commenced with the processes that are used to treat the sludge from purification and pumping stations; mostly Zuikerbosch and Vereeniging. The data gathered included the raw sludge, chemicals and electricity used, land use, water consumption, transport services and other inputs. The environmental releases identified and quantified were as follows:

- Water recovered and returned to the Vaal River and Zuikerbosch.
- Solid and liquid waste for disposal on a landfill site.
- Emissions to air and soil.

The amount of waste generated was evaluated in terms of the type and class of landfill disposal and quantified per unit weight of sludge input.

4.3.2.4.3 Data collection at the booster stations

The data collection at the booster stations was done similarly as for the purification and pumping system. The input flows to boost up potable water from the purification and pumping stations are:

- Available water to the boosters (Palmiet, Mapleton, Zwartkopjes and Eikenhof).
- The electricity used at the booster station.
- Chemicals used.
- Land usage.

The electricity is mostly required to boost up potable water to the higher altitude for the supplied water to gravitate from the reservoirs thereafter to the Rosslyn industrial area. Data on chemicals is also included at this stage as an additional input. Each stage of the booster stations was examined by evaluating the energy and material consumptions, the air emissions and water effluent, as well as the waste generated. The environmental outputs for each stage of booster stations were reported and averaged from on-site investigation data.

The indirect outputs, i.e. losses, were assumed from the booster system to the reservoir system. Accidental release and spills data during the operations were evaluated and reported in units of weight and included the substances regarded as pollutants per unit of the output generated or reference flow of the unit process. Finally, an estimation of how much land is used for this operation was calculated in terms of the space provided per annual production cycle.

4.3.2.4.4 Data collection on electricity production

Electricity is the main input requirement to produce and supply potable water to the end-consumer. The information gathered for this unit process is therefore extremely important from an energy consumption and environmental releases perspective. Eskom primarily supplies the electricity used. The typical South African electricity mix is shown in Figure 13 (Eskom, 2002). The figure also shows the source of compiled inventory data for electricity usage. A detailed inventory database has been compiled for all the electricity generation technologies (TEAM LCA, 2002).

The amount (and quality) of coal used, water and land use are the main input flows for electricity production. The output flows of electricity production from coal, which is shown in Figure 13 to be the most important generation process, include fly ash, flue gas desulphurisation sludge that results from air quality control measures through existing emission control devices and a variety of air pollutants.

Water effluents were reported in units of weight and include all the substances regarded as pollutants per unit of the reference flow. This includes all waste effluents that contain the number of substances that are still present in the waste stream after waste treatment. Data was recorded in terms of the discharges into the receiving waters.

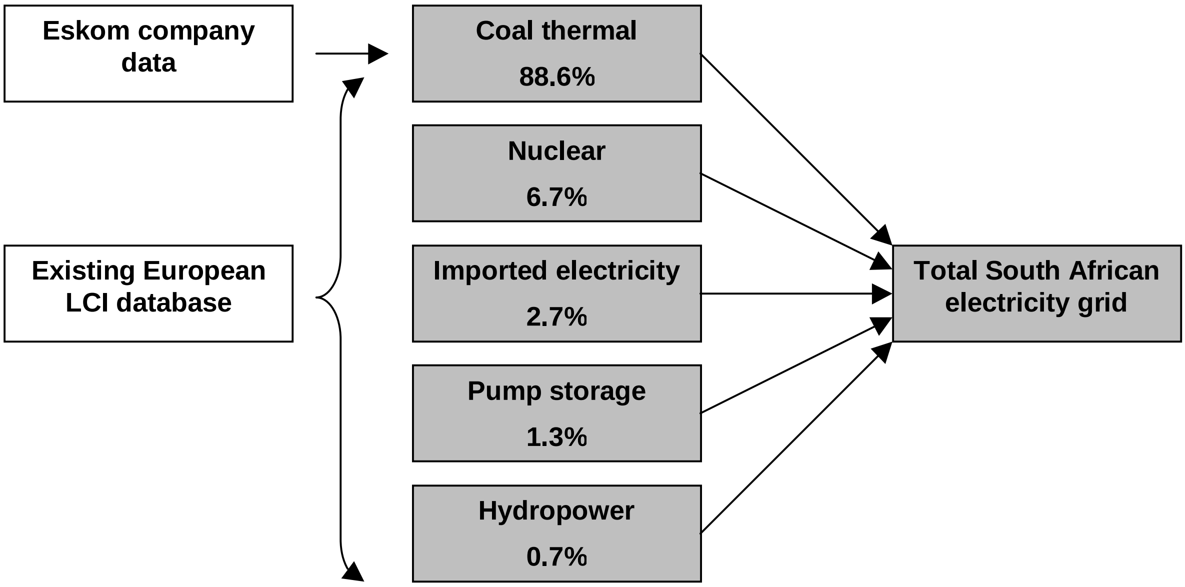


Figure 13: Sources of LCI data for the South African electricity generation mix

4.3.2.4.5 Data collection on reservoirs

Data collection on the reservoir system commenced with the potable water volume requirements in the Tshwane municipal district, which is reported in megalitres per day (daily average), month or year.

Losses (amount of potable water unaccounted for) between reservoirs were also recorded from the potable water that is supplied by Rand Water. The amount of potable water that goes in is the amount of water pumped from the booster to the reservoir or from one reservoir to another. The amount of water that goes out is the amount of water gravitated to the Rosslyn industrial area. The capacities of the different reservoirs were recorded and included in the inventory data sheets. At this stage assumptions were needed to estimate the land use input because of data gaps at municipality level. Furthermore, additional input flows of the sub-system were excluded that may have to be included in the inventory data sheets if required by a system boundary expansion, e.g. construction and maintenance material and energy requirements.

4.3.2.4.6 Calculation procedures

Following the data collection, calculation procedures are needed in order to generate the results of the inventory of the defined system for each unit process and for the defined functional unit of the product system that is modelled (ISO, 1998:9). The inventory contains the intrinsic calculations (e.g. a unit process mass balance, co-product and recycle allocation, a functional unit normalisation and, typically, a system-wide aggregation), efficiencies and items needed to achieve a relative system-wide approach to interpretation (ISO, 1998).

The calculations were done according to the functional unit of the system in order to understand which data is needed for the inventory analysis and which is of minor importance. Furthermore, as stipulated above, quantitative input and output data of the unit processes were established and calculated in relation to the functional unit of the water supply life cycle system. Where data was not obtainable for some of the processes, data from literature was used. By using calculations within a unit process, it is possible to decide or determine whether a single variable makes a small or a large contribution.

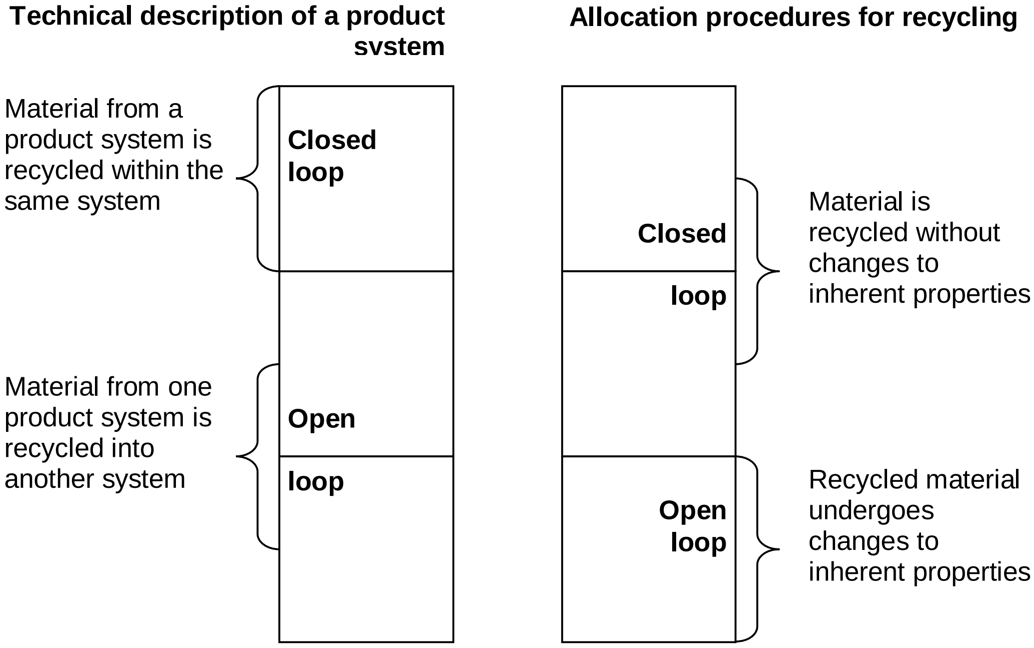
The land requirement (land use occupation in m^2.a degraded) data was estimated in terms of the capacity of the reservoir and the space provided per annual supply. The result is to quantify how much of land is occupied as industrial usage (Brent, 2003:118).

4.3.2.4.6.1 Allocations of flows and releases

LCI relies on being able to link unit processes within a product system by simple material or energy flows (ISO 1998:11). A number of methodological approaches have been published in the past for the allocation of environmental burdens of processes, which contribute to more than one product system (Frischnecht, 2000:176). The economic value is often used as the criterion for allocation. Thereby, the commercial value is used to allocate discharges generated within processes and for the life cycle as a whole; in this case to select which of the effluents are allocated to the production and supply of potable water to the Rosslyn industrial area.

The environmental impacts are consequently related to the economic effects (costs) of the system. For example, with regard to the energy production, the generated electricity is used as an input in the production and supply of potable water. The commercial value of the electricity is positive to the system despite the discharges generated during the unit process. Where the value of the electricity is substantial compared to the entire system, allocation is performed. For instance, the environmental impacts of the entire system may be allocated to the electricity required to produce and supply potable water. Then this unit process within the system may become a point of concern and its relative influence may be estimated, as well as the environmental impacts in terms of costs. Consequently, it affects a substantial part of the system cost in terms of production and supply of potable water. Furthermore, it may limit the economic feasibility of the overall system and would necessitate an environmental improvement.

Besides the economic value as a criterion, consideration must also be given to recycling, where open and closed-loop recycling occurs (see Figure 14). Allocation procedures should be uniformly applied to similar inputs and outputs of the system under consideration (ISO, 1998:11). Only the environmental burdens associated with the closed-loop recycling within the water supply system were included in this study, as is illustrated in Figure 14. The procedure is that the material is recycled without changes to inherent properties. For example, at the Panfontein sludge treatment plant, the clear supernatant water recovered during the treatment process can be as high as 90 to 95% of the raw sludge volume, and is recycled to Zuikerbosch for reprocessing with the raw water. The disposal credits (effluent) are allocated to the raw sludge that gets treated and the supernatant water that is recycled for reprocessing.

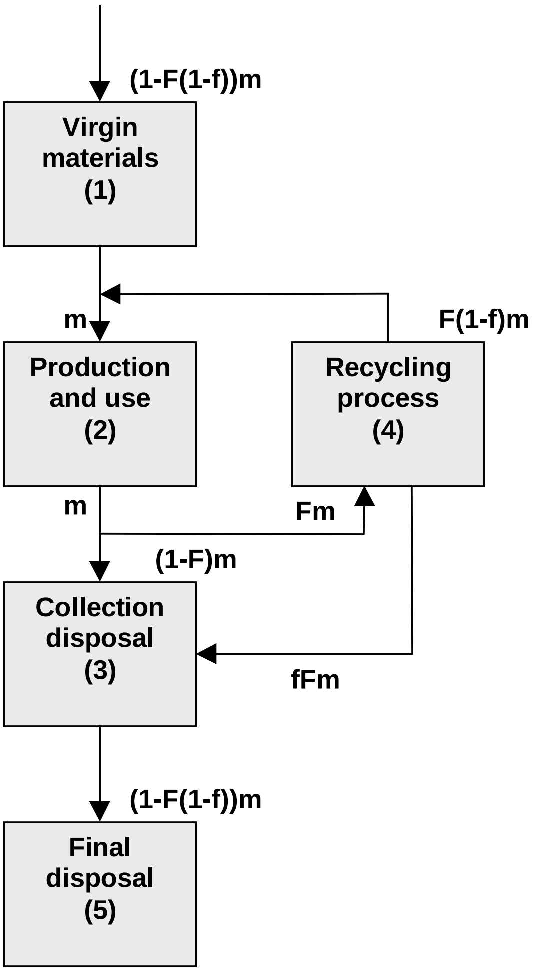


Source: ISO, 1998:12

Fig 14: Distinction between a technical description of product system and allocation procedure for a recycling

Consider an example where raw water extracted (Operation 1) is augmented with a portion of the recycled supernatant (F) to yield a total inflow (m) to produce potable water at Rand W Water works. The sludge is treated and recycled through the recycling process, and then (1-F) m is collected for reprocessing with the raw water from Vaal Dam. A fraction (f) of thickened sludge collected from the recycling process (4) is rejected for economic reasons (low demand for its use) and sent for disposal. Thus, the clear supernatant water recovered during the recycling process is recycled back tot the input flow to augment the raw water. The total disposal mass is (1-F (1-f)) m. The amount of the clear supernatant water recovered and recycled back is F (1-f) m. The concept is illustrated in Figure 15.

Figure 15: Closed-loop recycling calculation procedures



Source: Vigon et al., 1993:88

4.3.2.5 Data validation

The data quality is analysed in terms of validity and reliability (i.e. the completeness, variability and uncertainty of the data). The validity is analysed in terms of the degree to which it is representative of the life cycle system (Guinee *et al*., 2001).

The information for the production and supply of potable water from Rand Water is representative and reliable for the life cycle system of water supply, as the data originates from direct facility measurements. Some of the data was based on indirect estimates from published documents. Comparing this estimated data with international LCI data validated the data collected from the literature source to a certain degree, especially for the electricity production. However, the environmental practices of the local industry probably differ to some degree from those in developed countries and significant uncertainty exists where data from international publications are used (Brent, 2003:116).

The data was further validated by conducting mass balances within the unit process in order to ascertain if the total inputs to the unit process equal the outputs, including the discharges. However, these balances may be inaccurate due to the quality of the obtained values.

4.3.2.5.1 Data gaps and assumptions

It is believed that gaps and omissions in the inventory data in LCAs are inevitable to some degree now and in the future. LCAs cannot cover all issues or every part of complex industrial systems and, therefore, LCAs will always be incomplete in some way (Owens, 1999:82) [89]. The following data gaps in the LCI are noted:

- Data on the electricity production from Eskom's annual report lacked information, such as trace elements emitted when burning coal and the complete list of inputs in the production of electricity.
- There was no exact data on the land usage within the Tshwane reservoir system. The estimated data poses a methodological problem since there is no exact information on the space provided for each and every reservoir.
- Data on the output flows of potable water from the Tshwane reservoir system was not available and estimation through calculation had to be used. This aspect poses major problems on water loss calculations.
- Chemical inputs for water purification were estimated and included in the inventory with data gaps on the number of chlorines used at the booster stations.
- Emissions to water and air at the booster stations had to be estimated because of the lack of information.

Furthermore, the following assumptions were made:

- Referring to Figure 8 in Section 2.2.1.2 of the Rand Water supply network from the Vaal Dam, it was assumed that only the routes that lead to Rosslyn industrial area were accountable in the inventory study.
- The potable water pumped to Palmiet is blended with Zuikerbosch and Vereeniging. In this study, it was assumed that Zuikerbosch plays a major role in this process. Raw water from Vaal Dam is processed at

Zuikerbosch only; therefore it constitutes the first stage of this research. Input and output flows of the Vereeniging purification and pumping station were subsequently not accountable in this study.

- The input and output flows of the raw water extraction unit process were assumed to be of minor impact in the current study.
- Electricity is supplied solely by Eskom.
- Panfontein's core business is the disposal of water works sludge produced as a by-product of the water purification process at Rand Water's Vereeniging and Zuikerbosch pumping stations. However, it was assumed that Panfontein receives water works sludge from Zuikerbosch pumping station only because Vereeniging is not part of the network system considered in this study.
- The disposal site on the Panfontein premises can be described as a general landfill site.
- For the energy consumption at Zuikerbosch plants, 6% is assigned to ZKB1, 12% to ZKB2, 35.6% to ZKB3, 44.8% to ZKB4 and 4b. It was assumed that every input at this life cycle stage can be multiplied according to this percentage.
- Any transportation requirements, e.g. for the supply of chemicals, occur via road (40t trucks) and the suppliers are within a 50km range of the applicable unit process.

All of these assumptions were tested through sensitivity analyses during the LCI phase of the LCA study (see Chapter 5).

4.3.2.6 Relating data and data aggregation

4.3.2.6.1 Relating data to the functional unit of the modelled life cycle

The calculation operations were mostly used for unit conversions, water losses and mass balances relating to the reference flow within the unit processes (see Appendix A). The quantitative input and output data were subsequently converted according to the functional unit of the overall life cycle, i.e. 1 megalitre of potable water supplied per day (see the goal and scope definition in Section 2). For example, the CO_2 emissions released by the electricity generation and supply unit process are reported per MJ of electricity supplied. Thereafter, with relation to the functional unit, the number of CO_2 emissions associated with electricity is reported per megalitre of potable water supplied to the Rosslyn industrial area per day.

4.3.2.6.2 Data aggregation

Data aggregation leads to the presentation of the inventory table, which is the collection of values for all inputs and outputs for all unit processes involved in a system (Friedrich and Buckley, 2002:30). For this LCI, the overall inventory table consists of three main parts (see Table 6):

- Water purification and pumping, including the waste treatment and disposal stage.

- Boosting system.
- Reservoir storage and gravitational system.

The quantitative inputs and outputs of the electricity generation and supply are not reported separately in the overall inventory table. As the electricity unit process is included in the system boundaries of the LCI, these inputs and outputs can be obtained from the electricity required (as shown in Table 6) and through a linear manipulation of the data in Appendix A. The water losses that occur along the supply system, and which translate to the inflow and outflow values of Table 6, are summarised in Figure 16.

		Constituent	Value	Unit	Comment
Purification and pumping, including waste treatment and disposal	**Inputs**	Raw water	1.292	Ml	Obtained from Vaal River
		Recovered water	0.019	Ml	Obtained from Panfontein
		Chemicals	0.209	t	See Table 7 and Appendix A
		Electricity	937.26	MJ	See Appendix A
		Land use	5466.080	m^2.a	See Appendix A
		Fuel	0.389	l	See Appendix A
	Outputs	Treated and pumped water	1.283	Ml	Pumped up to the booster stations
		Solid/liquid waste	0.021	Ml	Sent to Panfontein landfill site
		Emergency discharges	0.027	Ml	Emergency discharge into water sources
		Dust fall out	0.667	g	See Appendix A
Boosting system	**Inputs**	Potable water received	1.27	Ml	See Figure 16
		Chemicals used	0.005	t	See Table 7 and Appendix A
		Electricity	811.906	KWh	See Appendix A
		Fuel	0.478	l	See Appendix A
		Land use	12.755	m^2	See Appendix A
	Outputs	Potable water pumped	1.265	Ml/d	See Figure 6 - pumped up to reservoirs
		Dust fall out	0.025	g	See Appendix A
Reservoir storage and gravitational system	**Inputs**	Received potable water	1.25	Ml/d	See Figure 16
		Land use	178.092	m^2	See Appendix A
	Outputs	Supplied potable water	1.0	Ml/d	Supplied directly to Rosslyn industrial area in the Tshwane municipal district

Table 6: Overall inventory for life cycle with relation to the functional unit

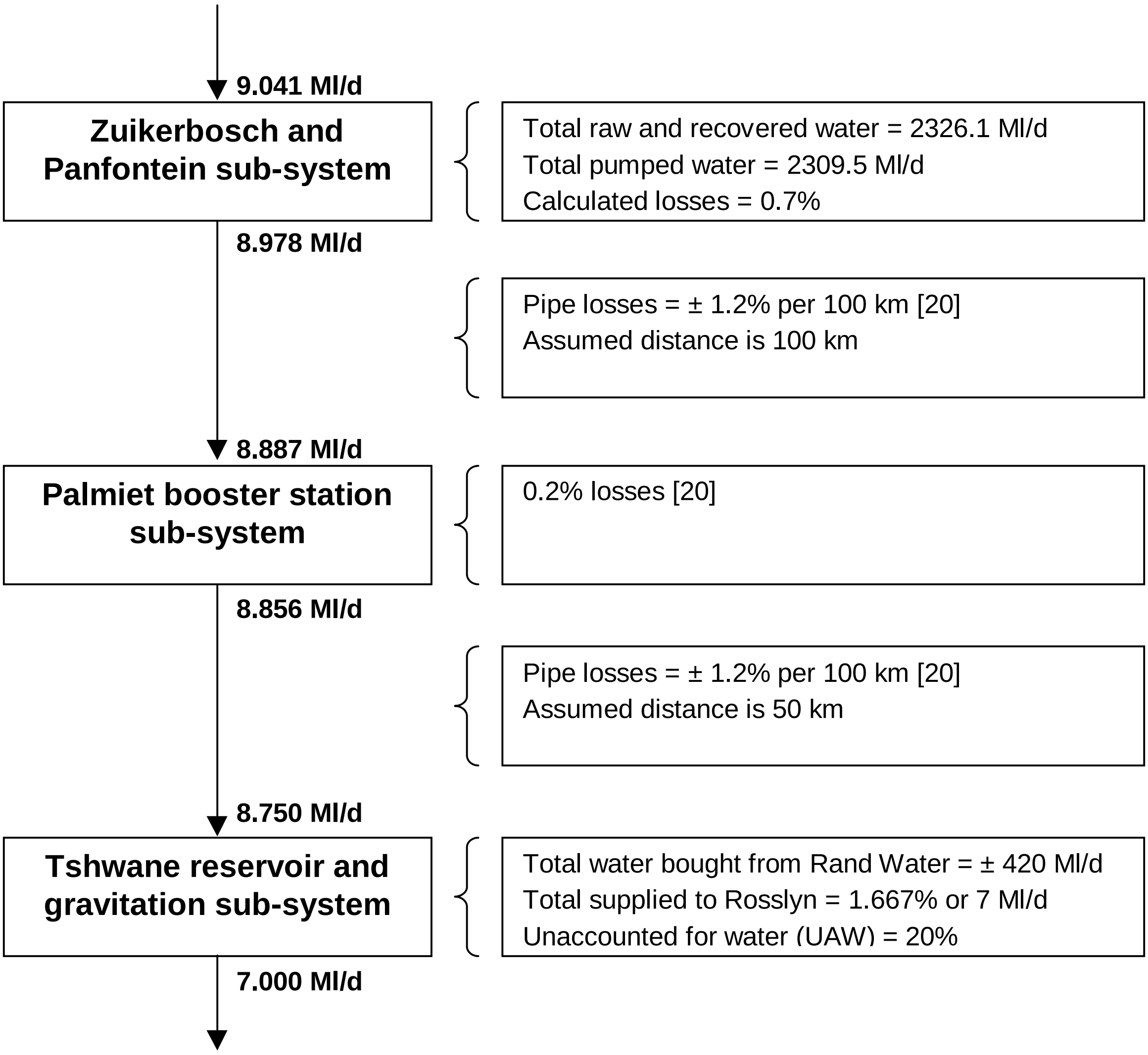


Figure 16: Water loss assumptions and calculated values

4.3.2.7 Refining the system boundaries

The initial product system boundaries were revised as appropriate in accordance with the cut-off criteria established in the goal and scope definition of the LCA study (see Section 2.2.3). In this regard the significance of an input stream to the overall system was determined through the relative mass-energy-economic (RMEE) boundary selection method (Raynolds *et al.,* 2000:39). However, only the mass and economic ratios of the input streams, in comparison to the functional unit, were considered. For example, if a chemical input stream is considered, the contribution of the input stream to the overall chemical input of the water use life cycle system is excluded if it has mass and economic ratios of less than 1% compared to the whole system (Brent and Hietkamp, 2003:29). Table 7 summarises the ratio comparisons of the input streams of the initial system of Figure 12.

	Input flow	Mass value (t)	Ratio (%)	Economic value (R)	Ratio (%)
Purification and pumping, including waste treatment and disposal	*Chemicals*				
	Burnt lime	0.031 (R 594.00/t)	0.0031	R 0.18	0.064
	Sodium silicate	0.00043 (R 766.50/t)	0.000043	R 0.33	0.12
	Ferric chloride	0.054 (R 653.90/t)	0.0054	R 35.31	**12.6**
	Chlorine	0.0025 (R 4092.67/t)	0.00025	R 10.23	**3.65**
	Polyamine	0.0904 (not known)	0.009	-	
	CO_2	0.019 (R 97.31/t)	0.0019	R 1.85	0.66
	Polyacrylamide	0.012 (R 15 765.00/t)	0.0012	R 189.18	**67.3**
	Fuel	0.00166 (R 0.0056/t)	0.00017	<< R 0.01	<< 0.01
Boosting system	*Chemicals*				
	Chlorine	0.002 (R 4 221.30/t)	0.0002	R 8.44	**3.00**
	Ammonia	0.003 (R 672.60/t)	0.0003	R 2.02	0.72
	Fuel	0.00076 (R 0.0056/t)	0.000076	<< R 0.01	<< 0.01

Table 7: RMEE calculation ratios in order to refine the system boundaries

From Table 7, the RMEE method indicates that the three input streams of ferric chloride, polyacrylamide and chlorine should be included in the boundaries of the life cycle. The detailed inventory data for the manufacturing and transportation to the water supply system were therefore included. However, as data availability is problematic in the South African context (see Section 2.4), international LCI databases were used for these chemicals, as provided in the TEAM LCA software databasis (TEAM LCA, 2002) (chlorine production) and the economic input-output databases of Carnegie Mellon University's Green Design Institute (EIOLCA, 2002) (ferric chloride and polyacrylamide). Fuel and ammonia were also included in the boundaries due to the availability of LCI data and to test the functionality of the RMEE method.

Sensitivity analyses were applied in the interpretation phase of the LCA to evaluate the uncertainty of the input data and to determine how changes in key parameters influence the results (Crettaz *et al.,* 1999:7). The overall analysis serves to limit the subsequent data handling to that input and output data that was determined to be significant to the goal of the LCA study (ISO, 1998:10). The sets of trials for the selected variables were chosen in order to run the simulations. The result of the sensitivity analysis appears to be as many inventories calculated as trials.

The data for each unit process was related to the functional unit of 1 megalitre of potable water supplied to Rosslyn and entered into the TEAM LCA software. A new graphical view for each unit process had to be drawn in this program.

Appendix B illustrates the modelled systems in the TEAM LCA software, whilst Appendix C provides a 'snapshot' of the baseline LCI for the functional unit of the LCA. Appendix I details the consistency check of the LCI data as this inventory snapshot will be used as a reference in the discussion and results phase of the study (Chapter 6).

4.3.3 Life Cycle Impact Assessment

4.3.3.1 Introduction

An overview of the LCIA phase of LCAs has been provided in Section 1.2.2.1.1. The experienced deficiencies of the available European LCIAs in the South African context have been discussed in Section 1.2.2.3 and an LCIA method for LCAs in South Africa has been introduced in Section 1.2.2.4.

4.3.3.2 The LCIA methodology that is applied

The LCIA methodology that has been developed for South Africa (Brent, 2003:117), and which is described in Section 1.1.3, was applied in the LCA study. The RII calculation procedure of the LCIA methodology requires current and target ambient state values for the classified impact categories (see Sections 1.1.3.3 and 1.1.3.4). These values are summarised in Table 5 for the defined SALCA regions in South Africa (see Figure 5).

Midpoint category and resource group impact	**Measurement units**	**Ambient annual values**	**SALCA Region 1**	**SALCA Region 2**	**SALCA Region 3**	**SALCA Region 4**
Water use (ground and surface water reserves) **(WU – water resources)**	kg of available reserves	**Current [t]**	1694×10^6	6598×10^6	2407×10^6	2562×10^6
		Target [t]	18×10^6	1123×10^6	1184×10^6	550×10^6
Eutrophication potential **(EP – water resources)**	kg PO_4^{3-} equivalence	**Current [t]**	462.5	1346.2	740.0	1560.6
		Target [t]	69.4	201.9	111.0	117.1
Acidification potential **(AP – air resources)**	kg SO_2 equivalence	**Current [kg]**	306.7	560.2	636.7	573.2
		Target [kg]	233.5	550.7	646.4	521.7
Acidification potential **(AP – water resources)**	kg H_2SO_4 equivalence	**Current [kg]**	5692.6	5239.7	3626.0	2412.5
		Target [kg][b]	7166.5	21108.4	11603.2	12235.1
Acidification potential[a] **(AP – land resources)**	kg H_2SO_4 equivalence	**Current [kg]**	5692.6	5239.7	3626.0	2412.5
		Target [kg][b]	7166.5	21108.4	11603.2	12235.1
Ozone creation potential **(OCP – air resources)**	kg O_3 formed	**Current [kg]**	466.2	1064.3	1209.7	1089.2
		Target [kg][b]	1167.3	2753.5	3232.1	2608.5
Ozone depletion potential **(ODP – air resources)**	kg CFC-11 equivalence	**Current [t]**	3754.8	3377.7	3405.0	9659.7
		Target [t]	2346.8	2117.9	2135.1	6057.0
Global warming potential **(GWP – air resources)**	kg CO_2 equivalence	**Current [Mt]**	1668.7	1505.9	1518.0	4306.5
		Target [Mt]	1600.5	1444.4	1456.1	4130.9
Human toxicity potential **(HTP – air resources)**	kg Pb equivalence	**Current [t]**	3.7	9.8	9.2	8.3
		Target [t]	2.9	6.9	8.1	6.5
Human toxicity potential **(HTP – water resources)**	kg Pb equivalence	**Current [kg]**	245125	242316	436600	257499
		Target [kg]	925	2692.4	1480	1560.6
Human toxicity potential **(HTP – land resources)**	kg Pb equivalence	**Current [t]**	5750	5189	5231	14840
		Target [t]	2168	1957	1973	5597
Aquatic toxicity potential **(ATP – water resources)**	kg Pb equivalence	**Current [kg]**	245125	242316	436600	257499
		Target [kg]	925	2692.4	1480	1560.6

[a] Values for land resources are currently considered to be equal to those of water resources in South Africa in order to preserve ecosystem quality.

[b] Target values reflect the capacity of the natural environment to sustain further burdens

Table 5: Current and target values for the classified impact categories

Table 5 (continued)

Midpoint category and resource group impact	Measurement units	Ambient annual values	SALCA Region 1	SALCA Region 2	SALCA Region 3	SALCA Region 4
Terrestrial toxicity potential **(TTP – land resources)**	kg Pb equivalence	**Current [t]**	5750	5189	5231	14840
		Target [t]	2168	1957	1973	5597
Occupied land use **(OLU – land resources)**	m^2.a near-natural[c]	**Current [ha]**	1.997×10^7	1.494×10^7	1.556×10^7	5.062×10^7
		Target [ha]	2.015×10^7	1.500×10^7	1.518×10^7	5.152×10^7
Transformed land use **(TLU – land resources)**	m^2 non-natural[d]	**Current [ha]**	3.453×10^6	6.229×10^6	5.889×10^6	9.852×10^6
		Target [ha]	3.279×10^6	6.170×10^6	6.270×10^6	8.953×10^6
Mineral depletion **(MD – mined resources)**	kg Pt equivalence	**Current [Mt]**	35529	35529	35529	35529
		Target [Mt]	16025	16025	16025	16025
Energy depletion **(ED – mined resources)**	kg coal equivalence	**Current [Mt]**	51813	51813	51813	51813
		Target [Mt]	24171	24171	24171	24171

[c] Area conserved in a pristine or near-pristine state of land degradation severity.

[d] Area transformed from a pristine or near-pristine state to another land use type degradation severity.

Source: Brent, 2003:119

4.4 Conclusion

The LCI is concerned with the data collection and calculation procedures to quantify inputs and outputs of a system respectively [3]. The goal of this study was to develop an LCI for the components included in this system. Information gathered for each and every unit process selected in the water system in terms of inputs and outputs related to the functional unit are included in the LCI profile table. Other necessary data was calculated using the daily statistics (monthly or annual report) at the Rand Water site.

The water loss calculation and assumptions, related to the functional units were made in order to estimate losses at pipe and reservoir levels during the water supply life cycle system . The cost of chemical materials such as chlorine, ferric chloride and polyacrylamide were significant in terms of the RMEE method so they were included in the boundaries of the life cycle system. LCI was used to generate the LCIA within the proposed framework for a South African LCIA procedure.

The analysis will be performed to determine the contribution of each and every unit process to the total environmental burdens of the water use system in the Rosslyn industrial area. The improvement efforts will then focus on the unit process, which makes a relatively substantial contribution to the result. This is the final part of the development of this study.

Chapter 5: Results, discussions and the interpretation of the LCA study

5.1 LCIA results

The LCIA results when applying the RII method to the baseline LCI ‘snapshot’ (of Appendix C) are summarised in Figure 17 and Table 8. The LCIA results are reported for SALCA Region 4, where the water is extracted and most of the main unit processes are located, SALCA Region 3, where the Rosslyn industrial area is located, and for South Africa as a whole.

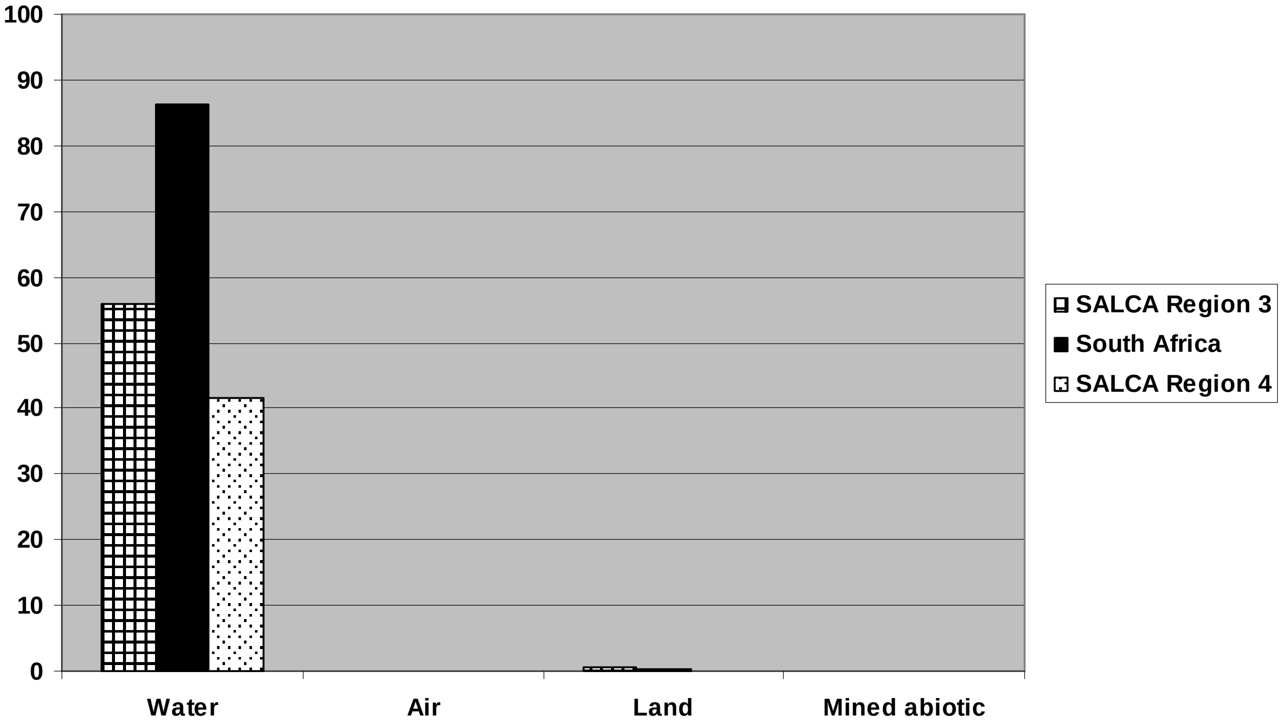


Figure 17: Calculated RIIs for SALCA regions 3, 4 and South Africa as a whole

Resource group	**Impact category[a]**	**Characterisation value**	**Unit[a]**	**Normalisation (SALCA Region 4)**	**Normalisation (South Africa)**
Water resources	**WU**	1.294×10^{6}	kg water reserves	3.346×10^{1}	8.424×10^{1}
	EP	2.726×10^{-1}	kg PO_4^{3-} eq.	3.103×10^{-5}	4.492×10^{-6}
	AP	9.810×10^{1}	kg H_2SO_4 eq.	1.581×10^{-3}	6.130×10^{-4}
	HTP	7.523×10^{1}	kg Pb eq.	7.954×10^{0}	2.005×10^{0}
	ATP	1.714×10^{-1}	kg Pb eq.	1.812×10^{-2}	4.567×10^{-3}
Air resources	**AP**	5.997×10^{0}	kg SO_2 eq.	1.263×10^{-2}	3.267×10^{-3}
	OCP	2.285×10^{-1}	kg O_3 eq.	3.657×10^{-5}	9.182×10^{-6}
	ODP	4.570×10^{-6}	kg CFC-11 eq.	1.203×10^{-12}	5.762×10^{-13}
	GWP	9.105×10^{2}	kg CO_2 eq.	2.298×10^{-10}	1.100×10^{10}
	HTP	1.984×10^{0}	kg Pb eq.	3.898×10^{-4}	1.033×10^{-4}
Land resources	**AP**	9.810×10^{1}	kg H_2SO_4 eq.	1.581×10^{-3}	6.130×10^{-4}
	HTP	2.805×10^{-1}	kg Pb eq.	1.329×10^{-7}	6.360×10^{-8}
	TTP	7.566×10^{-2}	kg Pb eq.	3.584×10^{-8}	1.716×10^{-8}
	OLU	4.463×10^{3}	m2.a near natural	2.599×10^{-2}	1.765×10^{-1}
	TLU	3.442×10^{0}	m2 non-natural	1.292×10^{-4}	5.834×10^{-4}
Mined abiotic resources	**MD**	9.26×10^{-8}	kg Pt eq.	5.197×10^{-13}	5.197×10^{-13}
	ED	5.469×10^{-1}	kg coal eq.	1.968×10^{-6}	1.968×10^{-6}

[a] Refer to Table 5 for the definitions of the impact categories and units of measurements.

Table 8: LCIA results for the baseline LCI snapshot

The normalised environmental profiles for each of the main resource groups are shown separately in figures 18 to 21. Furthermore, contribution analysis results are summarised in Table 9 in terms of:

- The most important impact categories in terms of contributions (of more than 1%) to the calculated RII values for the four main resource groups.
- The most important inventory flows or constituents in terms of contributions (of more than 1%) to the respective impact categories.
- The associated unit processes, i.e. the unit processes that contribute to more than 99% of the inventory flow values.

With respect to the overall environmental profile, the impacts on water resources are by far the most important consideration, i.e. the impacts on water resources are at least a factor of 40 compared to the impacts on the other resource groups. However, the total impact on water resources is not only attributable to water extraction. The release of toxic substances by the system, and specifically the generation of the required electricity for the LCA, may also be important with respect to the toxicity potential impact categories, i.e. in the order of 20% for the SALCA Region 4.

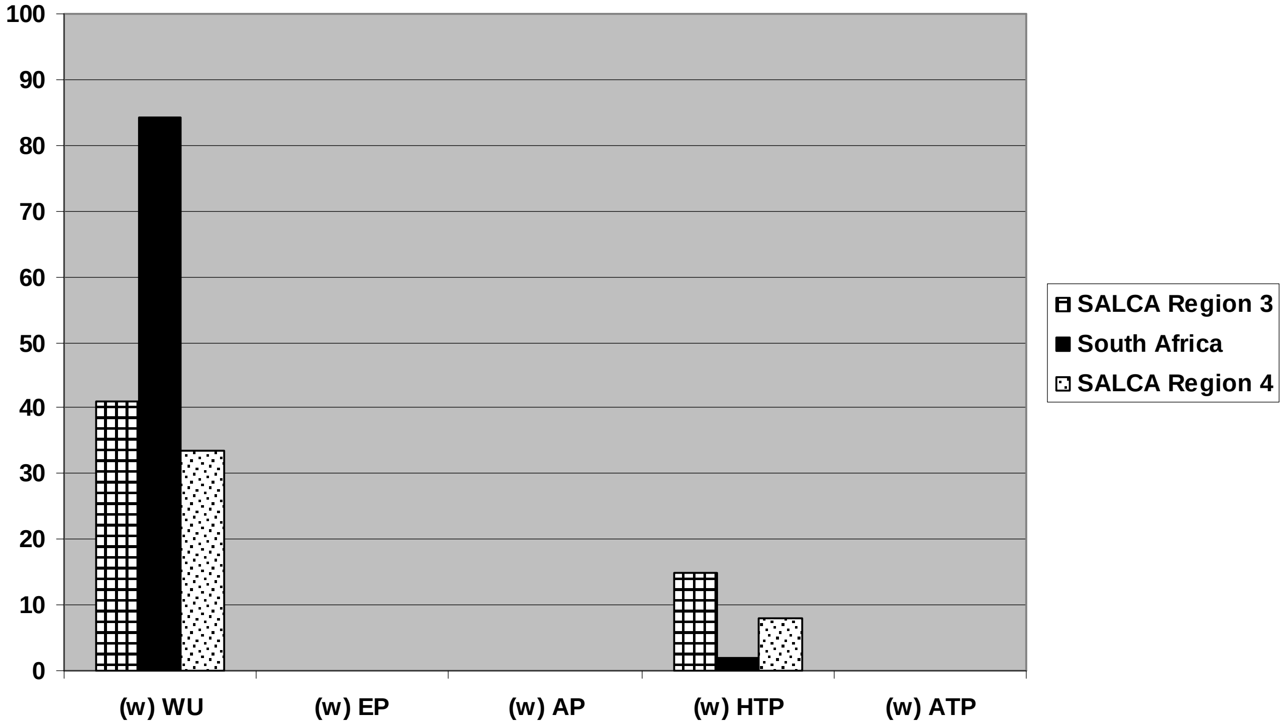


Figure 18: Water RII profile for SALCA regions 3, 4 and South Africa as a whole

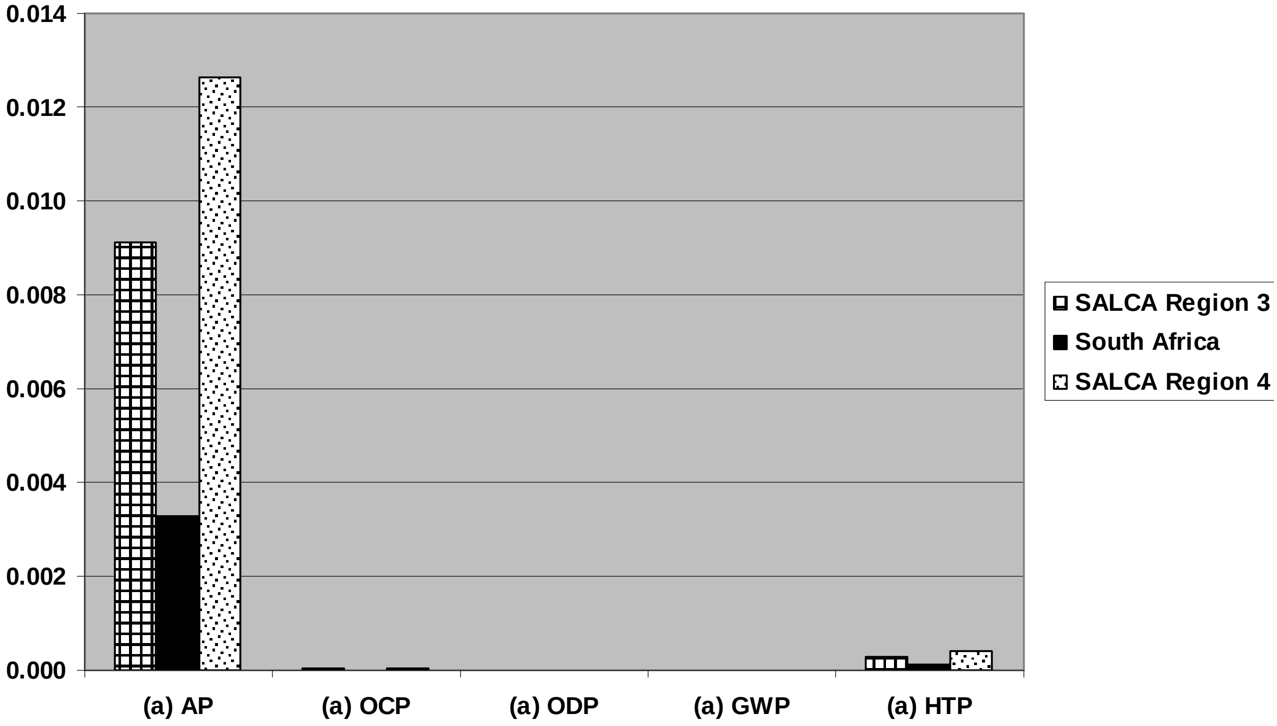


Figure 19: Air RII profile for SALCA regions 3, 4 and South Africa as a whole

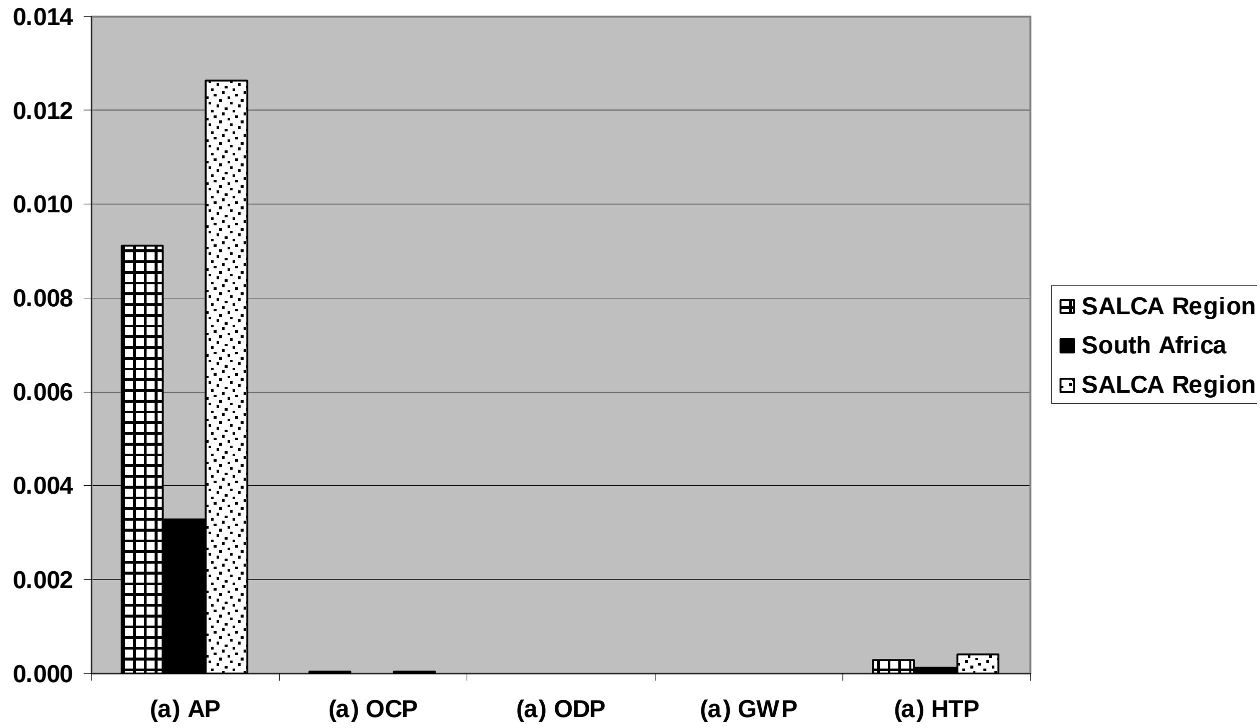


Figure 20: Land RII profile for SALCA regions 3, 4 and South Africa as a whole

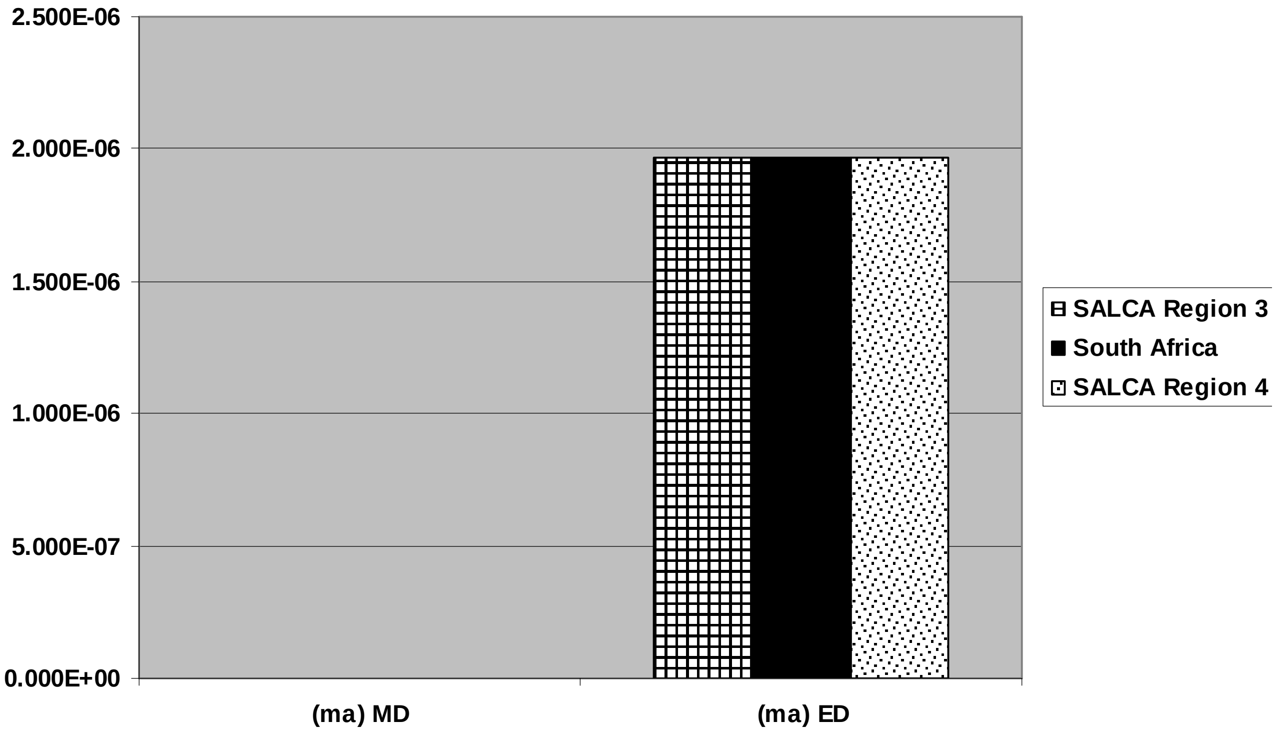


Figure 21: Mined abiotic RII profile for SALCA regions 3, 4 and South Africa as a whole

Table 9: Contribution analyses of the RII profiles

RII group	Impact category	% Contribution to RII group[a]	LCI constituent	% Contribution to impact category[b]	Unit process in LCA system	% Contribution to LCI constituent[c]
Water	**WU**	80.75 (97.67)	Water: River	99.83	Water extraction	100.00
	HTP	19.20 (2.33)	Arsenic (a)	6.72	Electricity	99.99
			Benzene (a)	1.35	Electricity	99.90
			Chromium (a)	79.74	Electricity	99.98
			HF (a)	4.87	Electricity	99.93
			Lead (s)	2.99	$FeCl_3$	97.41
					PAA	2.36
Air	**AP**	96.73 (96.67)	HCl (a)	6.41	Electricity	99.93
			NO_x as NO_2 (a)	24.03	Electricity	97.37
			SO_x as SO_2 (a)	68.70	Electricity	97.89
	HTP	2.99 (3.06)	Arsenic (a)	6.69	Electricity	99.98
			Benzene (a)	1.34	Electricity	99.90
			Chromium (a)	79.53	Electricity	99.98
			HF (a)	4.84	Electricity	99.93
			Lead (s)	2.97	$FeCl_3$	97.41
					PAA	2.36
Land	**OLU**	93.83 (99.33)	Industrialised[d]	95.57	Treatment[e]	99.84
			Urbanised[d]	4.43	Reservoirs	100.00
	AP	5.71 (0.34)	NO_x as NO_2 (a)	2.27	Electricity	97.37
			SO_x as SO_2 (a)	97.05	Electricity	97.89
Mined abiotic	**ED**	100.00 (100.00)	Coal	97.49	Electricity	99.80
			Natural gas	1.35	Electricity	74.78
					Ammonia	20.94
					Chlorine	1.20
			Oil	1.16	Electricity	37.50
					Ammonia	27.87
					Fuel	28.14
					Chlorine	5.09
					Diesel	1.38

a Only impact categories that contribute more than 1% to the respective resource groups are shown in the table; values without parentheses are normalised with SALCA Region 4 factors and values with parentheses are normalised with South African factors.

b Only LCI constituents that contribute more than 1% to the respect impact categories are shown.

c Only unit processes in the LCA system that contribute more than 1% to the respective LCI constituents are shown.

d Land occupied as existing extremely industrialised or urbanised land (Brent, 2003:118).

e Includes water purification, treatment and waste disposal.

5.2 Interpretation of the results

5.2.1 Identification of significant issues

The identification of significant issues is based on the results of the LCIA results for the baseline life cycle inventory snapshot and the contribution analyses of the RII profiles.

Depending on the water availability in the specific analysed region, water extraction is accountable for at least two-thirds of the total impact on water resources, for SALCA Region 3, and at least three-quarters for SALCA Region 4. It must be noted that considerable water losses of more than 20% are associated with the baseline LCI. However, by even removing all of these losses, the impact on the available quantity of water resources would still be more than double that of water quality impacts, if SALCA Region 4 is taken as the reference ambient environment, and can be as much as 25 times as important as the water quality impacts if the whole of South Africa is taken as reference region.

After water resources, the impacts on land resources are the most important for the system. However, the impact on land resources is at least four times lower than the impacts on water quality. Of all the impact categories classified to land resources, the occupation of land directly by the water purification and waste treatment, boosting and reservoirs supply system, is the main contribution to this impact category.

In general, the impacts on air resources are the third most important, although the acidification potential (for air) may be in the same order of magnitude compared to land usage if SALCA Region 4 is used as reference region. The release of atmospheric emissions that contributes to the acidification potential impact category, due the generation of the required electricity, makes the largest contribution to the impacts on air resources, i.e. at least 97%. Similar to water resources, the release of certain substances may also be of importance from a toxicity potential perspective.

The impacts of the water supply system on the depletion of non-renewable minerals and energy are considered insignificant.

Based on these findings, the following preliminary conclusions are reached from the LCIA:

- The extraction of the required water from nature to supply potable water to Rosslyn is in fact the most important consideration.
- Water quality impacts may also be important, although through supporting processes, i.e. electricity generation. Certain releases from the system, e.g. emergency discharges from the purification step (see

Table A1 of Appendix A) are not taken into account in the LCIA, which should be investigated further.

- The impacts of the required chemicals of the water supply system, i.e. ammonia, chlorine, ferric chloride, polyacrylamide, etc. are of low importance.
- The required non-renewable energy resources to pump the water from the Vaal River to the reservoir system are of minor importance.

These conclusions, however, must be tested in the interpretation phase of the LCA.

5.2.2 Evaluation

5.2.2.1 Completeness check

The completeness of the relevant information and data needed for the interpretation are available and complete in order to satisfy the goal and scope of the LCA (Section 2.2) and LCI (Section 3.2). With respect to this specific study, Table 10 highlights the missing or incomplete information and data that could influence the results of the LCA study.

Although these data gaps have been identified, it is believed that the available information is of relevance, such that the necessary interpretation could be conducted and conclusions reached. Especially for the LCI data gaps, these gaps have been addressed through the sensitivity check (see Section 5.1.2). With respect to the LCIA data gaps, however, no quantitative uncertainty analyses have been performed. It must be emphasised that the accuracy of the impact assessment methods have been questioned and in many cases the calculated impact indicators reflect a worst-case scenario (Ross *et al.,* 2002:48). The LCIA results must, therefore, be interpreted as a potential environmental indicator profile, rather than actual impacts associated with the water supply system.

LCA phase	Aspect	Comments
LCI	The usage of existing standard LCI databases	For certain unit processes, e.g. transportation, chlorine and ammonia production, etc, available databases from Europe were used as available in the TEAM LCA software, i.e. no site-specific information was used. These databases may be inappropriate in the South African context.
	The adaptation of existing standard LCI databases	For certain unit processes, e.g. electricity generation and distribution, available databases from Europe were adapted with company-specific information, as provided through environmental reports, etc. However, not all the data in these comprehensive databases could be checked and verified for the South African context.
	The application of non-standard LCI databases	For certain unit processes, i.e. the manufacturing and supply of ferric chloride and polyacrylamide, no standard LCI databases were available, and no company-specific information could be obtained. For these two unit processes specific economic input-output data from the USA were used. These types of databases provide general inflows and outflows per economic sector, using the USA as geographical boundary. The data is therefore most probably inappropriate for South Africa.
LCIA	Applied European characterisation factors of impact categories	For most impact categories, e.g. acidification potential, toxicity potential, etc., European characterisation factors were used directly. These factors are based on models that either focus on Europe, the northern hemisphere or, in some cases, the entire globe. The importance of region-specificity in the South African context would not be reflected in these characterisation factors.
	Categorisation and characterisation of LCI constituents	Certain LCI constituents, i.e. emergency discharges during the water purification step, are considered important by the water-supplying sector, and these parameters are consequently measured on a continuous basis. However, with the available chemical analysis results of these streams, and the nature of the LCI requirements of the impact categories, it was not possible to categorise these streams appropriately and they are subsequently not taken into account in the LCIA.
	Available impact categories and characterisation factors	Certain impact categories have not been established formally for LCAs, e.g. salinisation, and for other impact categories, e.g. water usage, no characterisation factors have been suggested as yet. This is considered the most important aspect that must be addressed in future water-related LCAs.

Table 10: Completeness check for this LCA

5.2.2.2 Sensitivity check

Based on the completeness evaluation, an uncertainty analysis has also been performed on the LCI constituents in order to determine whether the results of the LCIA would be significantly influenced by any LCI uncertainties. The uncertainly analyses were conducted as prescribed by the TEAM LCA software:

- Where a range of data is available for an LCI constituent, a min-max analysis is performed.
- Where only singular data is available for an LCI constituent, the Monte-Carlo statistical analysis is performed and a statistical distribution for each of the parameters is therefore assumed.

With respect to this LCA study, the following uncertainty analyses were performed:

- The electricity usage is a reasonably accurate value from company reports, and the LCI databases have been adapted with South African data (see Table 10). Therefore, the uncertainty of electricity usage was assumed to follow a normal distribution with a standard deviation of 10% of the median. A Monte-Carlo analysis was subsequently performed on all electricity inputs to the water supply system (see Appendix D).
- The transportation and other chemical unit processes have a high uncertainty (see Table 10). Therefore, normal distributions of these inputs were assumed with a standard deviation of 30% of the median. Monte-Carlo analyses were then performed on all of these inputs to the life cycle system (see Appendices E and F).
- The land usage of the main unit processes were assumed (see Appendix A) and are therefore also of a high uncertainty. A Monte-Carlo analysis with a normal distribution and 30% standard deviation was subsequently conducted for these input streams (see Appendix G).
- The amount of sludge that is treated at Panfontein reportedly ranges from 35 to 40 Ml/d, which therefore also influences the amount of recovered water that is sent back to Zuikerbosch. An aggregate of 37.5 Ml/d was used for the LCI, and a min-max analysis was therefore performed on the amount of sludge that is treated (see Appendix H).

Based on the findings of the sensitivity analyses of these LCI parameters, it is concluded that the LCI uncertainties will not have a significant influence on the interpretation outcomes of the LCIA and contribution analyses (Chapter 4).

5.2.2.3 Consistency check

A consistency check determines whether the assumptions, methods and data are consistent with the goal and scope of the study (see Chapter 2 and

Section 3.2 of Chapter 3). The categories that must be checked are (ISO, 2000:6):

- data source;
- data accuracy;
- data age;
- technical level;
- geographical representation; and
- technical level of the data.

5.2.2.3.1 Data source

The data sources and related quality issues are summarised in Table 11. Data on the main unit processes of the water supply system were either obtained from on-site interviews and published data (Rand Water), or from interviews only (Tshwane water supply infrastructure). Existing generalised European and American LCI databases were used for all auxiliary processes, except for the electricity generation and distribution data, which has been updated with South African specific information.

Lifecycle step	Subsystem	Source of data	Description	Quality	Comments
Extraction of raw water	Vaal River site	Vaal river site reports	Most data was known and published	Ö	Data is reasonably representative and complete with respect to the goal and scope of this LCA study.
Water treatment	Zuikerbosch site	Zuikerbosch site and Rand Water annual reports	Most data was known and published	Ö	
Sludge treatment plant	Panfontein site	Panfontein site reports	Most data was known and published	Ö	
Booster pumping station	Palmiet site	Palmiet site reports	Most data was known and published	Ö	
Electricity used	Rand Water site	Rand Water annual reports	Most data was known and published	Ö	
Electricity production	Eskom	International databases, Eskom annual reports	Generalise data was known and published	Ö	
Reservoir and gravitation	Palmiet site, Tshwane municipality	Municipality, CTMM report	Most data was known but not published	´	Data that was provided is questionable and problematic for LCA usage.
Rosslyn connection	Tshwane, Rosslyn industrial area water flows	Tshwane municipality, CTMM report, billing consumptions for Rosslyn	Most data was known but not published	´	
Chemicals	Zuikerbosch and Panfontein sites	International databases	Generalised data was published only	´	

Table 11: Data sources and related quality issues of the LCA study

5.2.2.3.2 Data accuracy

A detailed process flow diagram, which was obtained from Rand Water, was used to develop the LCI data site-by-site for Zuikerbosch, Panfontein, Palmiet and the reservoir and gravitation system (see Appendix A). The data for Zuikerbosch and Panfontein was reported accurately on a monthly basis. For booster stage and the reservoir and gravitation system, certain data had to be assumed and is therefore not accurate. Especially the water losses were based on personal observations and views in the industry sector. All data was aggregated on an annual basis for the functional unit.

5.2.2.3.3 Data age

All the data associated with the main unit processes has been obtained for the period 2002 to 2004. Where generalised LCI data was used, the data age is dependent on individual studies from the mid-1990s onwards.

5.2.2.3.4 Temporal representation

The LCI data on the main unit processes is based on the current technologies associated with the water supply system. The data on chemicals production, such as chlorine and ammonia, is typically based on recently developed technologies, while the polyacrylamide and ferric chloride production processes are described as a mixture of industrial inorganic and organic chemicals production technologies, from the applied economic input-output (EIO) LCA database, which includes recently built and old plants.

With respect to the LCIA, the normalisation values for the impact categories reflect the current and target state of the ambient natural environmental for the SALCA regions from 1990 to 2001, depending on the availability of ambient environmental data, as available in the public domain (at the beginning of 2002). Some of this data has been revised.

5.2.2.3.5 Geographical representation

The obtained LCI data for the main unit processes of the water supply system is entirely representative of the case study. The LCI data of the auxiliary processes are representative of Europe and the USA, except for electricity generation and distribution, which was updated with South African specific information. The aggregated data is therefore not accurate in the South African context, and especially for the respective South African value chains.

The LCIA method that was used, i.e. the RII calculation procedure, focuses on specific SALCA regions in South Africa. Although the region-specificity of the LCIA phase is thereby improved, the LCIA results are not representative of actual local impacts, i.e. as stated in Section 5.1.1, only a potential environmental profile associated with the water supply system is provided with the RII procedure.

5.2.2.3.6 Technical level of the data

The data associated for the life cycle stages that are managed by Rand Water, was established at plant level and is of good technical quality. The data for the reservoir and gravitation system, as managed by the Tshwane municipality, is a mixture for specific reservoirs and for the municipal infrastructure as a whole, and the quality is therefore not as good. The technical level of the data for the auxiliary unit processes depends on the specific LCI databases, which vary in terms of the quality thereof.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

In general, the assumptions made for this LCA study are considered relevant and appropriate to gather the LCI data and to establish the potential LCIA profile associated with water use in the Rosslyn industrial area, in line with the goal and scope of the LCA study.

Based on the LCI and LCIA outcomes, the following main conclusions are reached:

- The actual extraction of the water from the ambient environment is in fact the most important consideration. The toxicity potential impacts on water resources, mainly due to the required electricity for the water supply system, are of secondary importance. However, the extent of the impact due to water extraction is not accurately reported in the water use category of the LCIA profile, due to the lack of appropriate categorisation factors. For example, ambient water quality may be influenced by the reduction of water quantities. Similarly, the uncertainty of the applied LCIA method and the resultant indicator profile was not included in the interpretation of the LCA study and is assumed to reflect a worst-case scenario as reported in literature (Ross *et al.,* 2002:47) [92].
- The compiled LCI database and associated LCIA profile are specific for the case study. Therefore, the results of the LCA study cannot be generalised for any other region within or for South Africa.

6.2 Recommendations

The recommendations of this dissertation include recommendations for environmental improvement based on the results and recommendations for further studies.

6.2.1 Recommendations for environmental Improvement

In order to improve the environmental performance of the water supply system, water-losses must be addressed foremost. What is required at this stage is a strategic planning regarding the extraction, use and conservation of water resources. Furthermore, to optimise all processes of water extraction and make them more efficient, the electricity and other energy inputs are also of importance, albeit to a lesser extent.

From these outcomes the following LCA recommendations for environmental improvement are made:

- The electricity, and other energy inputs, is also of importance, albeit to a lesser extent.

- Additional case studies are required for the other major industrial centres of South Africa, whereby similar LCI databases and LCIA profiles can be established and general conclusions reached.
- The LCIA method must be developed further for South Africa, especially in terms of impacts on water resources. In this respect characterisation factors should be developed and/or adapted for South Africa, e.g. for water usage, acidification potential, toxicity potential and salinisation potential categories. Furthermore, normalisation factors for these categories must be established by a larger South African focus group, which represents the different environmental science disciplines and with international participation.
- Improve the monitoring on water resources in order to prevent them from being over abstracted and depleted. The licences issued from water affairs for example should show the date and the annual quantities that can be taken out of Vaal River in this case. Last but not least, determine the present status of water uses in the manufacturing industries with reference to existing water licensing rights. This approach, for instance, will be more beneficial to save on consumptive water use.
- The volume of runoff and the various rates of flow are vital statistics to water resources both surface and groundwater collecting system. The Vaal River equipped with outlets to the plant treatment, should have recording-level gauges and calibrated channels so that flows can be monitored and calculated. Once the equipment is installed and calibrated, it is necessary to accumulate readings that can be correlated with other meteorological data, in order to obtain meaningful water balance and avoid over extraction of water resources.

6.2.2 Recommendations for further studies

This research study has provided valuable insight into the application, practicability and requirements of the LCA tool for decision-support. Firstly, the importance of South African capacities and competencies in industry to conduct LCAs must be realised:

- Applying the thinking process of LCA during the design or operational stages of facilities in industry will lead to the identification of environmental performance and cost improvements. This is associated with the principles of cleaner production, which form part of the international sustainable production and consumption trends. Also, with respect to conducting LCAs during the design stages of undertaken projects, certain environmental improvements can be identified early in the project management life cycle and relevant environmental information can be available at the commencement of EIAs, which are required for many development projects in industry. This could have positive cost implications for project management practices.
- Globalisation and increasing pressures on value chains to improve environmental performance require that LCA-type data must be available as a competitive advantage. South African companies must, therefore, be in a position to be able to provide LCA information associated with their products and processes.

Considering this requirement of developing capacities and competencies in South Africa, however, highlights certain barriers that must be overcome:

- More students at university-level must be exposed to LCAs, especially engineering and natural science students. At present, this occurs haphazardly at different institutions around the country, and the education activities should be formalised. For example, the Engineering Council of South Africa (ECSA) requires that specific aspects or modules must be addressed in engineering degrees for accreditation, and LCAs could be incorporated into certain modules. Thereby, identified shortcomings of the LCA tool can also be addressed through dedicated research efforts. In this respect there is too little exposure of South African researchers to international LCA activities, i.e. the development of LCA methodologies through the UNEP global life cycle initiative and the incorporation of LCAs into management sciences whereby management decision-making practices can be improved.
- Companies are generally reluctant to participate in LCA activities, which are open to transparent review, due to perceived risks of information misuse and public criticism of environmental performances. This can be addressed in two stages. Firstly, government policy and strategy can target industry sectors to provide LCI information through, for example, the promotion of the Access to Information Act, No. 2 of 2000. Secondly, similar to current LCA activities in the USA, Europe and Australia, EIO databases can be developed for South Africa. These databases focus on entire industry sectors for the country as a whole, and company-specific information is therefore omitted.

The shortcomings of the LCIA phase of the LCA tool were specifically identified during this research, and especially with respect to the impacts on water resources. To this end the international LCA community has requested South African participation, but no concerted effort has been made from within South Africa. This can be addressed by the WRC through solicited research in order to:

- Develop LCIA midpoint categories for water resources for South African regions, and specifically characterisation and normalisation factors for these impact categories. The characterisation and normalisation factors should focus on the receiving environment, in line with the current legislation developments. The process should attempt to incorporate the available environmental sciences expertise in the country.
- Develop comprehensive water supply LCI databases for the different South African regions.
- Develop EIO LCA databases, based on these developed LCIA methods and LCI databases. Such EIO LCA databases would be more practicable for cleaner production purposes in industry.

The abovementioned efforts must be published for the larger South African community in order to stimulate further participation and local LCA development, e.g. in the *South African Journal of Science*. Also, very few LCA research outputs in South Africa are published for the global LCA community, e.g. in the *International Journal of Life Cycle Assessment*. This should be a requirement of future LCA funded projects.

REFERENCES

1. Allen DT, Consoli FJ, Davis GA, Fava JA, Warren JL (editors) (1997) *Public policy applications of life cycle assessment*. Society of Environmental Toxicology and Chemistry (SETAC), SETAC Press, Brussels.
2. Bare JC, Hofstetter P, Pennignton DW, de Haes HAU (2000) Midpoints versus endpoints: the sacrifices and benefits. *The International Journal of Life Cycle Assessment*, 5 (6), 319-326.
3. Basson MS, van Niekerk PH, van Rooyen JA (1997) *Overview of water resources availability and utilisation in South Africa*. Department of Water Affairs and Forestry (DWAF) report P RSA/00/0197, Pretoria.
4. Baumann H (1996) LCA use in Swedish industry. *The International Journal of Life Cycle Assessment*, 1 (3), 122-126.
5. Baumann H, Tillman AM (1999) *The hitchhiker's guide to LCA*. Technical Environmental Planning, Chalmers University of Technology, Göteborg.
6. Braunschweig A, Bär P, Rentsch C, Schmid L, Wüest G (1998) *Bewertung in ökobilanzen mit der methode de ökologischen knappheit: ökofaktoren 1997*. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Switzerland.
7. Brent AC (2002) *Management of imported supply chain products – Incorporating country-specific sustainability criteria in life cycle decision analysis*. Going Green, CARE Innovation 2002, Fourth International Symposium, International (S)CARE Electronics Office, Austrian Society for Systems Engineering and Automation, Vienna.
8. Brent AC (2003) A proposed lifecycle impact assessment framework for South Africa from available environmental data. *South African Journal of Science*, 99 (3/4), 115-122.
9. Brent AC (2004) A Life Cycle Impact Assessment procedure with resource groups as Areas of Protection. *The International Journal of Life Cycle Assessment*, 9 (3), 172-179
10. Brent AC (2002) *Developing country-specific impact procedures – Human health and ecosystem quality as criteria for resource quality and availability*. Presentation on the In LCA-LCM E-conference, American Centre for Life Cycle Assessment, Washington DC.
11. Brent AC (2002) Personal communications with the Water Quality Institute, Department of Water Affairs and Forestry, Pretoria.
12. Brent AC, Hietkamp S (2003) Comparative evaluation of Life Cycle Impact Assessment methods with a South African case study. *The International Journal of Life Cycle Assessment*, 8 (1), 27-38.
13. Brent AC, Rohwer MB, Friedrich E, von Blottnitz H (2002) Status of Life Cycle Assessment and Engineering research in South Africa. *The International Journal of Life Cycle Assessment*, 7 (3), 167-172.
14. Broberg O, Christensen P (1999) LCA experiences in Danish industry. *The International Journal of Life Cycle Assessment*, 4 (5), 257-262.
15. Brent AC, Visser JK (2005) An Environmental Performance Resource Impact Indicator for Life Cycle Management in the manufacturing industry. *Journal of Cleaner Production*, 13 (6), 557-565
16. Brentrup F, Küster J, Lammel J, Kuhlmann H (2002) Life Cycle Impact Assessment of land use based on the Hemeroby concept. *The International Journal of Life Cycle Assessment*, 7 (6), 339-348.

17. Chevalier J, Rousseaux P (1999) Classification in LCA – Building of a coherent family of criteria. *The International Journal of Life Cycle Assessment*, 4 (6), 352-356.
18. City of Tshwane (2004) *Foldout map*. http://www.tshwane.gov.za/SubContent.asp?id=294.
19. Consoli FJ, Allen DT, Boustead I, Fava JA, Franklin W, Jensen AA, de Oude N, Parrish R, Perriman R, Postlethwaite D, Quay B, Séguin J, Vigon B (editors) (1993) *Guidelines for life-cycle assessment: A code of practice*. Society of Environmental Toxicology and Chemistry (SETAC), SETAC Press, Brussels.
20. Cowell SJ, Clift R (2000) A methodology for assessing soil quantity and quality in life cycle assessment. *Journal of Cleaner Production*, 8, 321-331.
21. Crettaz P, Jolliet O, Cuanillon JM, Orlando S (1999) Life Cycle Assessment of drinking water and rain water for toilets flushing. *Aqua Volume*, 48 (3), 73-83.
22. CSIR (2002) *Water quality on disc*. Department of Water Affairs and Forestry's National Water Quality Monitoring Network, Environmentek, CSIR, Pretoria.
23. CSIR, ARC, Department of Environmental Affairs and Tourism (DEAT) (2002) *National land-cover database for South Africa*. GIS database, CSIR, Pretoria.
24. CSIR, ARC, Department of Environmental Affairs and Tourism (DEAT) (2002) *National land-cover database for South Africa*. GIS database, CSIR, Pretoria.
25. Department of Water Affairs and Forestry (DWAF) (1996): *South African water quality guidelines – Volume 7: aquatic ecosystems*. First edition, Directorate of Water Quality Management, The Government Printer, Pretoria.
26. Department of Water Affairs and Forestry (DWAF) (1996) *South African water quality guidelines – Volume 1: domestic use*. First edition, Directorate of Water Quality Management, The Government Printer, Pretoria.
27. Erlandsson M, Lindfors LG (2003) On the possibilities to apply the results of an LCA disclosed to public. *The International Journal of Life Cycle Assessment*, 8 (2), 65-73.
28. Eskom (2002) *Embracing sustainable development*. Environmental report 2001, http://www.eskom.co.za/, South Africa.
29. Finnveden G (2000) On the limitations of life cycle assessment and environmental systems analysis tools in general. *The International Journal of Life Cycle Assessment*, 5 (4), 229-238.
30. Finnveden G, Andersson-Sköld Y, Samuelsson MO, Zetterberg L, Lindfors LG (1992) Classification (impact analysis) in connection with life cycle assessment – a preliminary study. In: *Product Life Cycle Assessment – Principles and Methodology*. Nordic Council of Ministers, Copenhagen.
31. Friedrich E (2001) *The Use of Life Cycle Assessment for the production of potable water.* School of Chemical Engineering, University of Natal.
32. Friedrich E, Buckley C (2002) *The use of Life Cycle Assessment in the selection of water treatment processes*. Water Research Commission (WRC) Report No.1077/1/02, Pretoria.
33. Frischnecht R (2000) Allocation in Life Cycle Inventory Analysis for joint production. *The International Journal of Life Cycle Assessment*, 4 (3), 175-179.
34. Goedkoop M (1996) *The eco-indicator 95 - Weighting method for environmental effects that damage ecosystems or human health on a European scale*. Company report, Pré Consultants B.V., Amersfoort.
35. Goedkoop M, Spriensma R (2000) *The eco-indicator 99 – a damage oriented method for life cycle impact assessment*. Company report, Pré Consultants B.V., Amersfoort.
36. Graedel TE (1998) *Streamlined life-cycle assessment*. Prentice-Hall International, Upper Saddle River, N.J.

37. Green Design Initiative (2002) *Economic Input-Output Life Cycle Assessment*. http://www.eiolca.net/, Carnegie Mellon, Pittsburgh.
38. Grotz S, Scholl G (1996) Application of LCA in German industry – results of a survey. *The International Journal of Life Cycle Assessment*, 1 (4), 226-230.
39. Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Sleeswijk AW, Suh S, de Haes HAU, de Bruijn H, van Duin R, Huijbregts MAJ (2001) *Life cycle assessment – an operational guide to the ISO standards*. Centre for Environmental Studies (CML), Leiden University, Leiden.
40. Hallman M., Grant T and Aslop N (2003) Yarra Valley: Life Cycle Costing of Water Tanks as a Supplement to Mains Water Supply. *Australian LCA Society.* Centre for design at RMIT University, Melbourne.
41. Hoffman T, Ashwell A (2001) *Nature divided – Land degradation in South Africa*. University of Cape Town Press, Cape Town.
42. International Organization for Standardization (ISO) (2003) *ISO 14000*. http://www.iso.org/iso/en/iso9000-14000/iso14000/iso14000index.html, Geneva.
43. International Institute for Sustainable Development (IISD) (1996) *Global green standards – ISO 14000 and sustainable development*. IISD, Winnipeg.
44. International Organization for Standardization (ISO) (1998) *Code of Practice: Environmental management – Life cycle assessment – Life cycle impact assessment*. Draft International Standard, ISO 14042: 1998, Geneva.
45. International Organization for Standardisation (ISO) (2004) *TC207 Environmental Management*. http://www.tc207.org, Geneva.
46. Institute of Soil, Water and Climate Sciences (2001) *Predicted concentrations of trace elements in South African soils*. Agricultural Research Commission report, Pretoria.
47. Jimenez-Gonzales C, Kim S, Overcash MR (2000) Methodology for developing gate-to-gate Life Cycle Inventory Information. *The International Journal of Life Cycle Assessment*, 5 (3), 152-159.
48. Kruger GP (1996) *Terrain Morphological Map of Southern Africa*. Agricultural Research Council's Institute for Soil, Climate and Water, Pretoria.
49. Labuschagne C (2003) *Sustainable project life cycle management*. Masters thesis, Department of Industrial and Systems Engineering, University of Pretoria, Pretoria.
50. Lindfors LG, Christiansen K, Hoffman L, Virtanen Y, Juntilla V, Hanssen OJ, Röning A, Ekvall T, Finnveden G (1995) *Nordic guidelines on life-cycle assessment*. The Nordic Council, Nord 1995:20, Copenhagen.
51. Low AB, Rebelo AG (1998) *Vegetation of South Africa, Lesotho and Swaziland*. South African Department of Environmental Affairs and Tourism (DEAT), ISBN 0621173169, Pretoria.
52. McClintock S (2000) *Strategic Environmental Management Plan for the Richards Bay SEA*. CSIR Environmentek report, JX01K, prepared for the Richards Bay Transitional Local Council Forward Planning Section, Pretoria.
53. Nations Environmental Programme (UNEP) (2000) *The Montreal Protocol on substances that deplete the ozone layer*. Ozone Secretariat, http://www.unep.org/ozone.
54. Neitzel H (1996) Principles of product-related life cycle assessment – Conceptual framework/Memorandum of understanding. *The International Journal of Life Cycle Assessment*, 1 (1), 49-54.
55. Owens WJ (1999) Why Life Cycle Assessment is now described as an indicator system. *The International Journal of Life Cycle Assessment*, 4 (2), 81-86.

56. Platinum Today (2002) *Production – Resources in South Africa*. http://www.platinum.matthey.com/production/africaResources.php.
57. PricewaterhouseCoopers (2002) TEAM LCA software database, Department of Engineering and Technology Management, University of Pretoria.
58. Raluy RG, Serra L, Uche J, Valero A (2005) Life Cycle Assessment of Water Production Technologies - Part 2: Reverse Osmosis Desalination versus the Ebro River Water Transfer. *The International Journal of Life Cycle Assessment*, online first < DOI: http://dx.doi.org/10.1065/lca2004.09.179.2>.
59. Rand Water Supply Board (2004) *Rand Water*. http://www.randwater.co.za/.
60. Rand Water Supply Board (2004) *Panfontein Sludge Disposal Site*. Rand Water internal report, Johannesburg.
61. Raynolds M, Fraser R, Checkel D (2000) The relative mass-energy-economic (RMEE) method for system boundary selection. Part 1: A means to systematically and quantitatively select LCA boundaries. *The International Journal of Life Cycle Assessment,* 5 (1), 37-48.
62. Raynolds M, Fraser R, Checkel D (2000) The Relative Mass-Energy-Economic (RMEE) method for system boundary selection. Part 2: Selecting the boundary cut-off parameter (ZRMEE) and its relationship to overall uncertainty. *The International Journal of Life Cycle Assessment*, 2 (2), 96-104.
63. Rebitzer G, Fullana P, Jolliet O, Klöpffer W (2001) Advances in LCA and LCM. *The International Journal of Life Cycle Assessment*, 6 (4), 187-191.
64. Rogers DEC, Brent AC (2001) *Laser-based remote measurement of atmospheric pollutants: phase 1: international requirements*. CSIR Innovation Fund report 8600/86DD/HTI12, Pretoria.
65. Rorich R, Galpin JS (1999) *Long-term trend analysis of ambient air quality in central Mpumalanga*. National Association for Clean Air, Annual Clean Air Conference, Cape Town.
66. Ross S, Evans D, Webber M (2002) How LCA studies deal with uncertainty. *The International Journal of Life Cycle Assessment*, 7 (1), 47-52.
67. Sampson I (2001) *Introduction to a legal framework to pollution management in South Africa*. Deloitte & Touche and Water Research Commission (WRC) report, no. TT 149/01, Pretoria.
68. Seppälä J (1999) Decision analysis as a tool for life cycle impact assessment. *LCA Documents*, 4, Ecomed publishers, Germany.
69. Sevitz J, Brent AC, Fourie AB (2003) An environmental comparison of plastic and paper consumer carrier bags in South Africa – Implications for the local manufacturing industry. *South African Journal of Industrial Engineering*, 14 (1), 67-82.
70. South African Bureau of Standards (SABS) (1998) *Code of Practice: Environmental management – Life cycle assessment – Principles and framework*. SABS ISO 14040: 1997, Pretoria.
71. South African Bureau of Standards (SABS) (1999) *Code of practice: Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis*. SABS ISO 14041: 1998, Pretoria.
72. South African Department of Environmental Affairs and Tourism (DEAT) (2000) *The National State of the Environment Report*. Directorate Environmental Information and Reporting, Pretoria.
73. South African Bureau of Standards (SABS) (2002) *Code of practice: Environmental management – Life cycle assessment – Life cycle interpretation*. SABS ISO 14043: 2000, Pretoria.

74. South African Department of Minerals and Energy (DME) (2002) *Coal Resources*. http://www.dme.gov.za/energy/coal_resources.htm.
75. South African National Government (2003) *Constitutional matters*. http://www.polity.org.za/html/govdocs/constitution/, Pretoria.
76. Steen B (1999) *A systematic approach to environmental priority strategies in product development (EPS) – version 2000 – general system characteristics*. Centre for Environmental Assessment of Products and Material Systems (CPM), Technical Environmental Planning, Chalmers University of Technology, Göteborg.
77. Stinnes LA (1995) *Life Cycle Inventory Analyses of the recycling processes of plastic bottle and film products in Germany and South Africa*. Masters thesis, University of Stellenbosch.
78. Suh S, Huppes G (2002) Missing inventory estimation tool using extended input-output analysis. *The International Journal of Life Cycle Assessment*, 7 (3), 134-140.
79. Terblanche P (1998) *Vaal Triangle air pollution health study – Bibliography, summary of key findings and recommendations*. National Urbanisation and Health Research Programme, Medical Research Council, Johannesburg.
80. Tibor T, Feldman I (1996) *ISO 14000 – A guide to the new environmental management standards*. Irwin, Chicago.
81. Troge A (2000) Life cycle assessment and product-related environmental policy. *The International Journal of Life Cycle Assessment*, 5 (4), 195-200.
82. Tukker A (1999) Life cycle assessment for waste, part I. *The International Journal of Life Cycle Assessment*, 4 (5), 275-281.
83. UNEP Industry and Environment (1999) *Towards the global use of life cycle assessment*. United Nations Publication Sales no. 92-807-1740-5, New York.
84. United Nations Environmental Programme (UNEP) (2002) *Convention on Biological Diversity – Convention text*. Secretariat of the Convention on Biological Diversity, http://www.biodiv.org/convention/articles.asp.
85. United Nations Environmental Programme (UNEP) (2003) *Global Life Cycle Initiative*. http://www.uneptie.org/pc/sustain/lcinitiative/, Geneva.
86. UNEP Sustainable Consumption (2004) *Life Cycle Inventory Programme*. http://www.uneptie.org/pc/sustain/lcinitiative/lci_program.htm, Geneva.
87. United Nations Framework Convention on Climate Change (UNFCCC) (2002) *The Convention and Kyoto Protocol*. http://unfccc.int/resource/convkp.html.
88. United States Environmental Protection Agency (EPA) (1997) *Pathway to product stewardship – Life-cycle design as business decision-support tool*. Pollution Prevention and Toxics, EPA742-R-97-008, Washington DC.
89. United States Environmental Protection Agency (USEPA) (2004) *LCA 101*. http://www.epa.gov/ORD/NRMRL/lcaccess/lca101.htm, USA.
90. Venter I (2004) Seven tenants settle in at new Gauteng auto hub. *Engineering News*, 24 (13), 18.
91. Vigon BW, Tolle DA, Cornaby BW, Lathan HC, Harrison CI, Boguski TL, Hunt RG, Sellers JD (1993) *Life Cycle Assessment: inventory guidelines and principles*. United states Environmental Protection Agency, Office of Research and Development, EA/600/R-92/245, Washington DC.
92. Vigon BW, Tolle DA, Cornaby BW, Lathan HC, Harrison CI, Bogusky TL, Hunt RG, Sellers JD (1993) *Life Cycle Assessment: Inventory guidelines and principles*. United States Environmental Protection Agency, Office of Research and Development, EA/600/R-92/245, Washington DC.

93. Water Research Commission (WRC) (2004) *Environmental Life Cycle Impact Assessment of water use in a selected industrial area of South Africa*. Memorandum of Agreement K5/1552//3, WRC Project no. 1552, Pretoria.
94. Water Research Commission (WRC) (2004) *Water SA*. Journal website, http://www.wrc.org.za/publications/watersa/default.asp.
95. Wenzel H, Hauschild M, Alting L (1997) *Environmental assessment products. Volume 1: Methodology, tools and case studies in product development*. Chapman & Hall, London.
96. Birkhead A L, Olbrich BW, James CS & Roger KH (1997)) *Developing an integrated approach to predicting water use of riparian vegetation.* WRC Report No. 474/1/97. ISBN: 1 86845 269 7 Water Research Commission, Pretoria, South Africa.

Appendix A: The environmental data sheets for the unit processes included in the water supply life cycle system

Flow	Value	Unit
Raw water (from Vaal River)	1.017	Ml/d
Recovered water (from Panfontein treatment facility)	0.015	Ml/d
Chemicals used:		
Burnt lime	2.4×10^{-2}	t/d
Sodium silicate	3.3×10^{-4}	t/d
Ferric chloride	4.2×10^{-2}	t/d
Chlorine	1.9×10^{-3}	t/d
CO_2	1.5×10^{-2}	t/d
Electricity used	0.205	MWh/d
Land occupied as existing industrialised land	4304	m^2/d
Fuel used (light fuel oil)	0.306	l/d
Solid/liquid waste (to be processed at Panfontein)	1.6×10^{-2}	Ml/d
Emergency discharges[a]	2.1×10^{-2}	Ml/d
Dust	1.2×10^{-4}	g/m^2/d
Treated water (received at Palmiet)	**1.00**	**Ml/d**

Non-periodic water releases; only pH of approximately 8, turbidity and alkalinity measured currently.

Table A1: Zuikerbosch purification and pumping system for 1Ml/d of potable water supplied to the booster (Palmiet) life cycle stage [A1, A2]

Flow	Value	Unit
Raw sludge (received from Zuikerbosch)	1.081	Ml/d
Chemicals used:		
Polyacrylamide	3.313	kg/d
Electricity used	0.270	kWh/d
Land occupied as existing industrialised land	162162.162	M^2/d
Fuel used (light fuel oil)	1.216	l/d
Dry sludge (for onsite waste disposal in a landfill)	16.216	t/d
Dust	68	mg/m^2/d
Recovered water (received at Zuikerbosch)	**1.00**	**Ml/d**

Table A2: Panfontein system for 1Ml/d of recovered water supplied to the Zuikerbosch purification and pumping system [A3]

Flow	**Value**	**Unit**
Potable (from Zuikerbosch purification system)	1.016	Ml/d
Chemicals used:		
Chlorine	0.816	kg/d
Ammonia	1.184	kg/d
Electricity used	649.524	kWh/d
Land occupied as existing industrialised land[a]	10.204	m^2/d
Fuel used (light fuel oil)[b]	0.382	l/d
Dust	5.7	$mg/m^2/d$
Potable water (received at Klipriviersberg)	**1.00**	**Ml/d**

[a] Assumed 1 hectare.a for 980 Ml/d

[b] Diesel density of 0.827 kg/l assumed

Table A3: Palmiet boosting system for 1Ml/d of potable water supplied to the Klipriviersberg reservoirs system [A1, A4, A5]

Flow	**Value**	**Unit**
Potable water (from Palmiet booster system)	1.25	Ml/d
Land occupied as existing extremely urbanised land[a]	178.09	m^2/d
Potable water (received at Rosslyn)	**1.00**	**Ml/d**

[a] Total land use for all the reservoirs in Tshwane is 65538 m^2.a for 460 Ml/d bought from Rand Water.

Table A4: Tshwane municipality reservoirs and gravitation system for 1Ml/d of water gravitated to Rosslyn [A6]

A1 Rand Water Supply Board (2002) *The dawn of a new era*. Rand Water annual report, Johannesburg.
A2 Rand Water Supply Board (2004) Monthly discharge report, Johannesburg.
A3 Rand Water Supply Board (2004) *Panfontein Sludge Disposal Site*. Rand Water internal report, Johannesburg.
A4 Rand Water Supply Board (2003) Palmiet monthly report, Johannesburg.
A5 Rand Water Supply Board (2001) Corporate Environmental Report, Johannesburg.
A6 City of Tshwane (2002) *City of Tshwane Metropolitan Municipality: A strategy and master plan for bulk water supply, storage and distribution*. Tshwane Metropolitan Municipality, Pretoria.

Appendix B: Flow diagrams and systems modelled in the TEAM LCA software

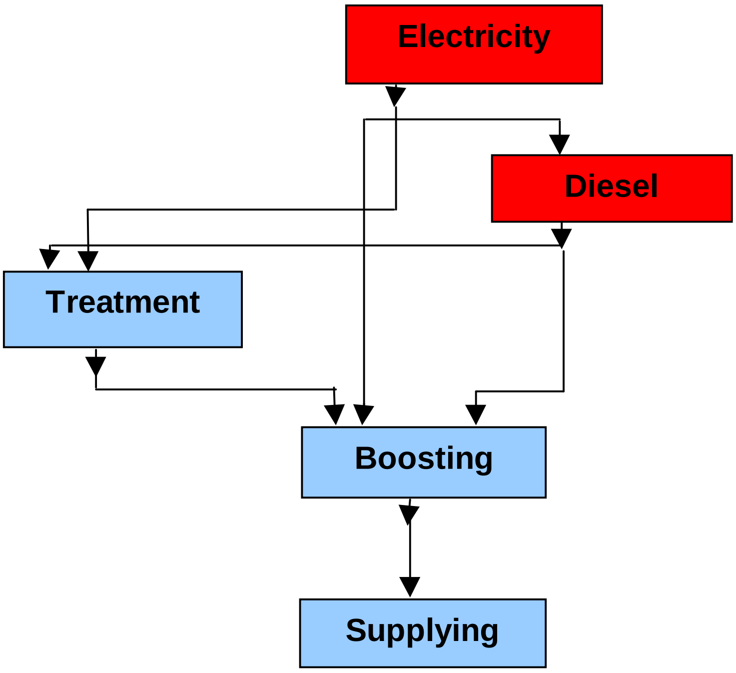


Figure B1: Overall water supply system

Diesel is produced for the road transport requirements of the treatment and boosting sub-systems. Electricity and diesel production has been taken directly from the supplied TEAM LCA software database.

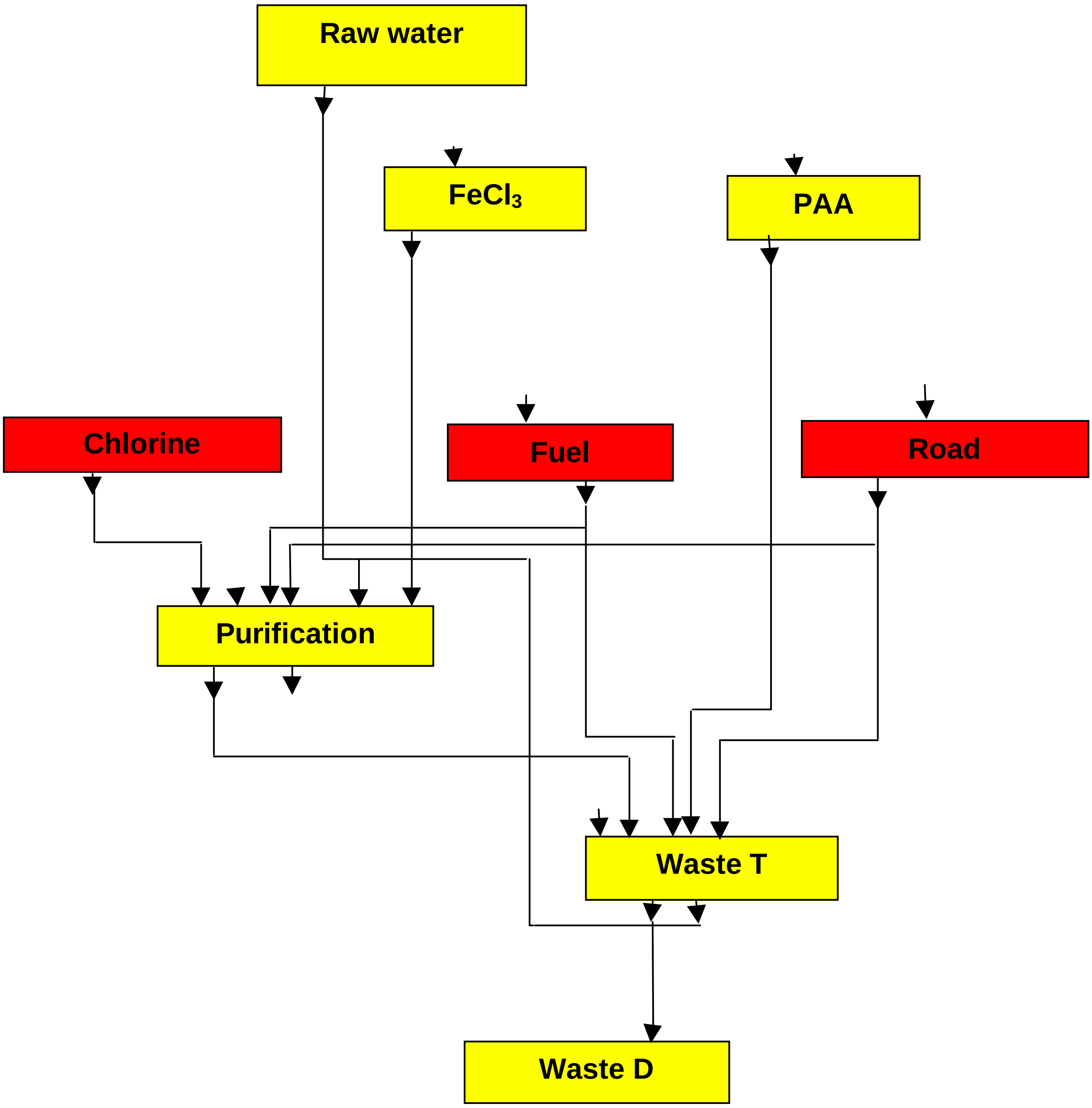


Figure B2: Water treatment sub-system (Zuikerbosch)

Chlorine and fuel production, and road transportation (40t trucks) has been taken directly from the TEAM LCA software database.

Road transport requirement is assumed to be 50 km for the supplied $FeCl_3$ and PAA.
$FeCl_3$ and PAA supply data is taken from available economic input-output databases.

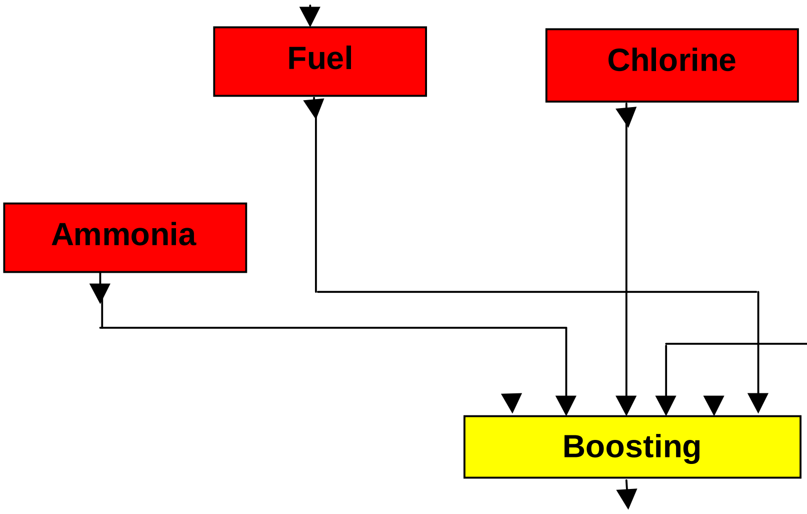


Figure B3: Boosting sub-system (Palmiet)

Ammonia, fuel and chlorine production and road transportation (40t trucks) is taken directly from the TEAM LCA software database.
Road transport requirement is assumed to be 50 km for the supplied $FeCl_3$ and PAA.

Appendix C: Snapshot of the baseline LCI of the modelled system

Flow	Compartment	Unit	Value
Inputs			
Barium sulphate	Mined abiotic	kg	4.874×10^{-4}
Bauxite	Mined abiotic	kg	7.791×10^{-1}
Bentonite	Mined abiotic	kg	1.510×10^{-5}
Calcium sulphate	Mined abiotic	kg	1.867×10^{-2}
Chromium	Mined abiotic	kg	1.740×10^{-6}
Clay	Mined abiotic	kg	1.218×10^{-1}
Coal	Mined abiotic	kg	6.541×10^{2}
Copper	Mined abiotic	kg	4.281×10^{0}
Dolomite	Mined abiotic	kg	1.100×10^{-5}
Feldspar	Mined abiotic	kg	1.720×10^{-6}
Fluorspar	Mined abiotic	kg	1.720×10^{-6}
Granite	Mined abiotic	kg	1.720×10^{-6}
Gravel	Mined abiotic	kg	2.550×10^{0}
Iron	Mined abiotic	kg	2.901×10^{-1}
Iron sulphate	Mined abiotic	kg	2.116×10^{-2}
Lead	Mined abiotic	kg	6.910×10^{-6}
Lignite	Mined abiotic	kg	3.727×10^{-1}
Limestone	Mined abiotic	kg	7.917×10^{-1}
Manganese	Mined abiotic	kg	1.420×10^{-8}
Natural gas	Mined abiotic	kg	6.289×10^{0}
Nickel	Mined abiotic	kg	1.720×10^{-6}
Oil	Mined abiotic	kg	3.504×10^{0}
Olivine	Mined abiotic	kg	6.940×10^{-6}
Phosphate rock	Mined abiotic	kg	3.430×10^{-6}
Potassium chloride	Mined abiotic	kg	1.195×10^{-1}
Pyrite	Mined abiotic	kg	2.010×10^{-4}
Sand	Mined abiotic	kg	5.724×10^{-2}
Silver	Mined abiotic	kg	6.080×10^{-10}
Sodium chloride	Mined abiotic	kg	3.959×10^{0}
Sulphur	Mined abiotic	kg	1.299×10^{-2}
Titanium	Mined abiotic	kg	1.720×10^{-6}
Uranium	Mined abiotic	kg	2.386×10^{-3}
Zinc	Mined abiotic	kg	1.720×10^{-6}
Land occupied (urbanised)	Land	m^2.a	3.450×10^{1}
Land occupied (industrialised)	Land	m^2.a	8.584×10^{3}
Land transformed (II->III)	Land	m^2.a	2.787×10^{0}
Land transformed (II->IV)	Land	m2.a	3.729×10^{-1}
Land transformed (III->IV)	Land	m^2.a	1.323×10^{-1}
Water: Total from public network	Water	litre	2.726×10^{3}
Water: River	Water	litre	1.291×10^{6}

Flow	Compartment	Unit	Value
Water: Sea	Water	litre	2.419×10^{-2}
Water: Well	Water	litre	6.200×10^{-4}
Outputs			
Acetaldehyde	Air	g	2.250×10^{-5}
Acetic acid	Air	g	5.065×10^{-4}
Acetone	Air	g	2.000×10^{-5}
Acetylene	Air	g	5.880×10^{0}
Aldehyde	Air	g	1.188×10^{-2}
Alkanes	Air	g	5.396×10^{0}
Alkenes	Air	g	5.880×10^{0}
Alkynes	Air	g	2.050×10^{-7}
Aluminium	Air	g	1.130×10^{2}
Ammonia	Air	g	2.290×10^{0}
Antimony	Air	g	2.350×10^{-2}
AOX	Air	g	9.420×10^{-11}
Aromatic hydrocarbons (unspecified)	Air	g	3.720×10^{-3}
Arsenic	Air	g	2.184×10^{-1}
Barium	Air	g	1.354×10^{0}
Benzaldehyde	Air	g	3.690×10^{-11}
Benzene	Air	g	8.013×10^{0}
Benzo(a)pyrene	Air	g	1.810×10^{-2}
Beryllium	Air	g	2.217×10^{-2}
Boron	Air	g	1.072×10^{1}
Bromium	Air	g	2.244×10^{0}
Butanes	Air	g	1.480×10^{-1}
Butenes	Air	g	3.636×10^{-3}
Cadmium	Air	g	1.420×10^{-2}
Calcium	Air	g	1.354×10^{1}
Carbon dioxide	Air	g	1.030×10^{6}
Carbon disulphide	Air	g	2.041×10^{-3}
Carbon monoxide	Air	g	1.413×10^{3}
Carbon tetraflouride	Air	g	2.970×10^{-8}
Chlorine	Air	g	2.833×10^{-3}
Chromium	Air	g	2.639×10^{-1}
Cobalt	Air	g	3.388×10^{-2}
Copper	Air	g	1.675×10^{-1}
Cyanide	Air	g	2.962×10^{-2}
Dichloroethane	Air	g	1.717×10^{-3}
Dioxins	Air	g	2.140×10^{-7}
Ethane	Air	g	2.182×10^{1}
Ethanol	Air	g	3.920×10^{-5}
Ethyl benzene	Air	g	3.636×10^{-3}

Flow	Compartment	Unit	Value
Ethylene	Air	g	4.844×10^{1}
Fluorides	Air	g	9.871×10^{-4}
Fluorine	Air	g	2.072×10^{-3}
Formaldehyde	Air	g	8.566×10^{-1}
Halon	Air	g	4.181×10^{-4}
Heptane	Air	g	3.635×10^{-2}
Hexane	Air	g	4.593×10^{-2}
Hydrocarbons (except methane)	Air	g	8.646×10^{1}
Hydrogen	Air	g	2.420×10^{0}
Hydrogen chloride	Air	g	5.362×10^{2}
Hydrogen cyanide	Air	g	2.041×10^{-3}
Hydrogen flouride	Air	g	1.928×10^{1}
Hydrogen sulphide	Air	g	$1.482\text{E}\times10^{1}$
Iodine	Air	g	5.358×10^{-1}
Iron	Air	g	4.524×10^{1}
Lanthanum	Air	g	3.560×10^{-2}
Lead	Air	g	6.318×10^{0}
Magnesium	Air	g	3.957×10^{1}
Manganese	Air	g	2.384×10^{-1}
Mercaptans	Air	g	2.782×10^{-3}
Mercury	Air	g	3.655×10^{-2}
Methane	Air	g	3.814×10^{3}
Methanol	Air	g	6.640×10^{-5}
Molybdenum	Air	g	4.388×10^{-2}
Nickel	Air	g	2.226×10^{-1}
Nitrogen oxides (as NO_2)	Air	g	2.513×10^{3}
Nitrous oxide	Air	g	1.121×10^{1}
Particulates	Air	g	8.185×10^{2}
Pentane	Air	g	1.852×10^{-1}
Phenol	Air	g	2.830×10^{-10}
Phosphorus	Air	g	9.980×10^{-1}
Phosphorus pentoxide	Air	g	6.771×10^{-4}
Polycyclic Aromatic Hydrocarbon (PAH)	Air	g	2.084×10^{-3}
Potassium	Air	g	1.354×10^{1}
Propane	Air	g	1.350×10^{1}
Propionaldehyde	Air	g	1.020×10^{-10}
Propionic acid	Air	g	1.290×10^{-7}
Propylene	Air	g	6.416×10^{0}
Scandium	Air	g	1.208×10^{-2}
Selenium	Air	g	2.144×10^{-1}
Silicon	Air	g	1.692×10^{2}

Flow	Compartment	Unit	Value
Sodium	Air	g	6.772×10^{0}
Strontium	Air	g	2.210×10^{0}
Sulphur oxides (as SO_2)	Air	g	5.595×10^{3}
Sulphuric acid	Air	g	2.042×10^{-3}
Thallium	Air	g	1.105×10^{-2}
Thorium	Air	g	2.278×10^{-2}
Tin	Air	g	7.119×10^{-3}
Titanium	Air	g	3.957×10^{0}
Toluene	Air	g	1.622×10^{0}
Uranium	Air	g	2.210×10^{-2}
Vanadium	Air	g	4.481×10^{-1}
Vinyl chloride	Air	g	1.725×10^{-3}
Volatile Organic Compounds (VOCs)	Air	g	1.306×10^{1}
Xylene	Air	g	1.085×10^{0}
Zinc	Air	g	6.814×10^{-1}
Zirconium	Air	g	1.692×10^{-2}
Aluminium	Land	g	1.601×10^{-3}
Arsenic	Land	g	6.400×10^{-7}
Cadmium	Land	g	2.890×10^{-10}
Calcium	Land	g	6.397×10^{-3}
Carbon	Land	g	4.802×10^{-3}
Chromium	Land	g	8.010×10^{-6}
Cobalt	Land	g	2.940×10^{-10}
Copper	Land	g	1.470×10^{-9}
Iron	Land	g	3.198×10^{-3}
Lead	Land	g	7.197×10^{0}
Manganese	Land	g	6.400×10^{-5}
Mercury	Land	g	5.330×10^{-11}
Nickel	Land	g	2.2100×10^{-9}
Nitrogen	Land	g	2.510×10^{-8}
Phosphorus	Land	g	8.010×10^{-5}
Sulphur	Land	g	9.596×10^{-4}
Zinc	Land	g	2.400×10^{-5}
Acids (as H^+)	Water	g	3.472×10^{-2}
Acrolein	Water	g	1.300×10^{-7}
Acrylonitrile	Water	g	2.270×10^{-5}
Aldehyde	Water	g	6.870×10^{-7}
Aldrin	Water	g	6.500×10^{-9}
Alkanes	Water	g	2.627×10^{-2}
Alkenes	Water	g	2.425×10^{-3}
Aluminium	Water	g	2.150×10^{0}
Aluminium hydroxide	Water	g	4.720×10^{-5}

Flow	Compartment	Unit	Value
Ammonia	Water	g	5.998×10^{0}
AOX	Water	g	2.139×10^{-3}
Aromatic hydrocarbons (unspecified)	Water	g	1.263×10^{-1}
Arsenic	Water	g	2.779×10^{-3}
Barium	Water	g	5.095×10^{-1}
Barytes	Water	g	2.269×10^{-2}
Benzene	Water	g	2.683×10^{-2}
Benzo(a)pyrene	Water	g	8.120×10^{-8}
BOD (5)	Water	g	6.602×10^{-2}
Boric acid	Water	g	6.029×10^{-2}
Boron	Water	g	3.233×10^{-3}
Bromates	Water	g	1.717×10^{-3}
Cadmium	Water	g	3.156×10^{-4}
Calcium	Water	g	7.219×10^{0}
Carbon disulphide	Water	g	2.192×10^{-4}
Carbonates	Water	g	2.387×10^{-1}
Cerium	Water	g	2.016×10^{-4}
Chlorates	Water	g	1.476×10^{0}
Chlorides	Water	g	5.829×10^{3}
Chlorine	Water	g	4.579×10^{-3}
Chlorobenzene	Water	g	7.310×10^{-5}
Chloroform	Water	g	3.870×10^{-9}
Chromate	Water	g	2.033×10^{-3}
Chromites	Water	g	8.520×10^{-6}
Chromium	Water	g	2.580×10^{-3}
Cobalt	Water	g	1.131×10^{-4}
COD	Water	g	4.097×10^{-1}
Copper	Water	g	2.791×10^{-3}
Cyanide	Water	g	8.495×10^{-1}
Dichloroethane	Water	g	1.717×10^{-3}
Dissolved Organic Carbon	Water	g	1.280×10^{-3}
Edetic acid	Water	g	1.023×10^{-4}
Ethyl benzene	Water	g	4.868×10^{-3}
Fluorides	Water	g	1.254×10^{0}
Formaldehyde	Water	g	1.460×10^{-5}
Hexachlorobenzene	Water	g	5.200×10^{-7}
Hydrazine	Water	g	4.700×10^{-5}
Hypochlorite	Water	g	1.160×10^{-6}
Hypochlorous acid	Water	g	1.160×10^{-6}
Iode	Water	g	2.019×10^{-2}
Iron	Water	g	1.712×10^{0}
Lead	Water	g	1.630×10^{0}

Flow	Compartment	Unit	Value
Lithium Salts	Water	g	5.250×10^{-6}
Magnesium	Water	g	4.191×10^{-1}
Manganese	Water	g	5.404×10^{-1}
Mercury	Water	g	2.044×10^{-3}
Methylene chloride	Water	g	1.110×10^{-5}
Molybdenum	Water	g	4.624×10^{-3}
Morpholine	Water	g	4.978×10^{-4}
Nickel	Water	g	4.427×10^{-2}
Nitrates	Water	g	4.118×10^{-1}
Nitrites	Water	g	2.880×10^{-7}
Nitrogenous matter	Water	g	2.381×10^{-2}
Organic Dissolved Matter	Water	g	6.076×10^{-3}
Oxalic acid	Water	g	2.047×10^{-4}
Phenol	Water	g	7.156×10^{-2}
Phosphates	Water	g	1.217×10^{-3}
Phosphorus	Water	g	8.284×10^{-4}
Phosphorus pentoxide	Water	g	2.019×10^{-2}
Polycyclic Aromatic Hydrocarbons	Water	g	8.973×10^{-3}
Potassium	Water	g	6.544×10^{0}
Rubidium	Water	g	2.019×10^{-3}
Selenium	Water	g	4.044×10^{-3}
Silicon dioxide	Water	g	3.980×10^{-6}
Silver	Water	g	1.212×10^{-4}
Sodium	Water	g	4.950×10^{2}
Strontium	Water	g	3.252×10^{0}
Styrene	Water	g	4.060×10^{-5}
Sulphates	Water	g	3.601×10^{2}
Sulphides	Water	g	5.320×10^{-3}
Sulphites	Water	g	1.510×10^{-4}
Suspended matter	Water	g	3.350×10^{1}
Tetrachloroethylene	Water	g	1.620×10^{-6}
Tin	Water	g	1.400×10^{-5}
Titanium	Water	g	2.478×10^{-3}
Total Organic Carbon (TOC)	Water	g	1.491×10^{0}
Toluene	Water	g	2.186×10^{-2}
Trichloroethane	Water	g	3.760×10^{-11}
Trichloroethylene	Water	g	1.620×10^{-6}
Triethylen glycol	Water	g	1.277×10^{-3}
Vanadium	Water	g	1.557×10^{-2}
Vinyl chloride	Water	g	1.731×10^{-3}
Volatile Organic Compounds (VOCs)	Water	g	7.192×10^{-2}
Xylene	Water	g	1.899×10^{-1}

Flow	Compartment	Unit	Value
Zinc	Water	g	4.725×10^{-2}
Waste (from water treatment)	Unspecified	kg	2.670×10^{7}
Waste (other total)	Unspecified	kg	4.939×10^{2}

Table C1: Life cycle inventory to supply 1 Ml/d of potable water to Rosslyn

Appendix D: Sensitivity analyses based on the uncertainty of electricity usage of the main unit processes

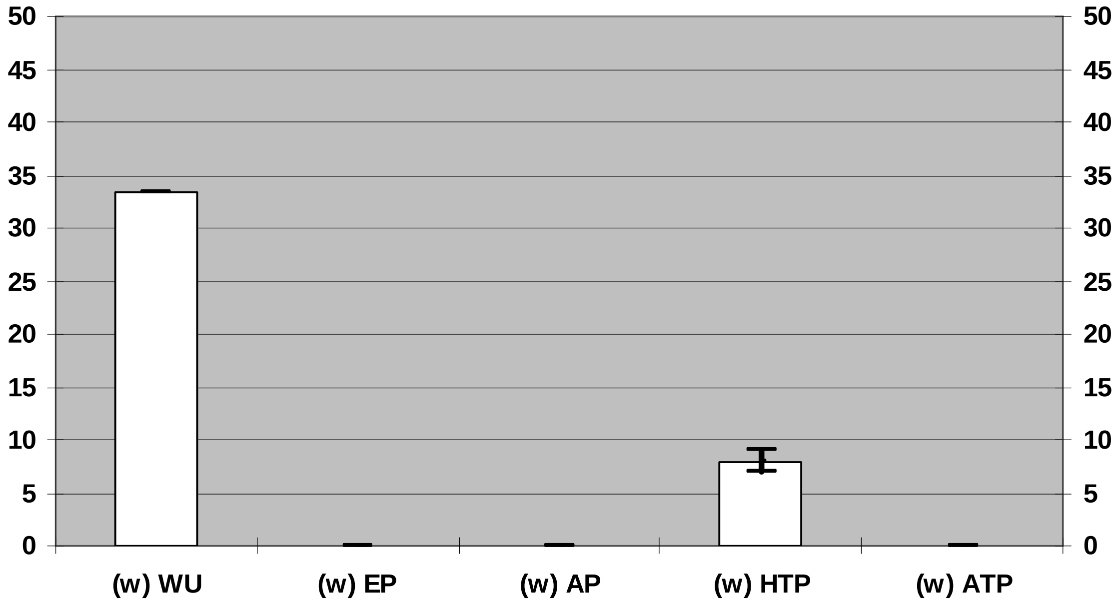


Figure D1: Sensitivity of the water RII profile to electricity usage

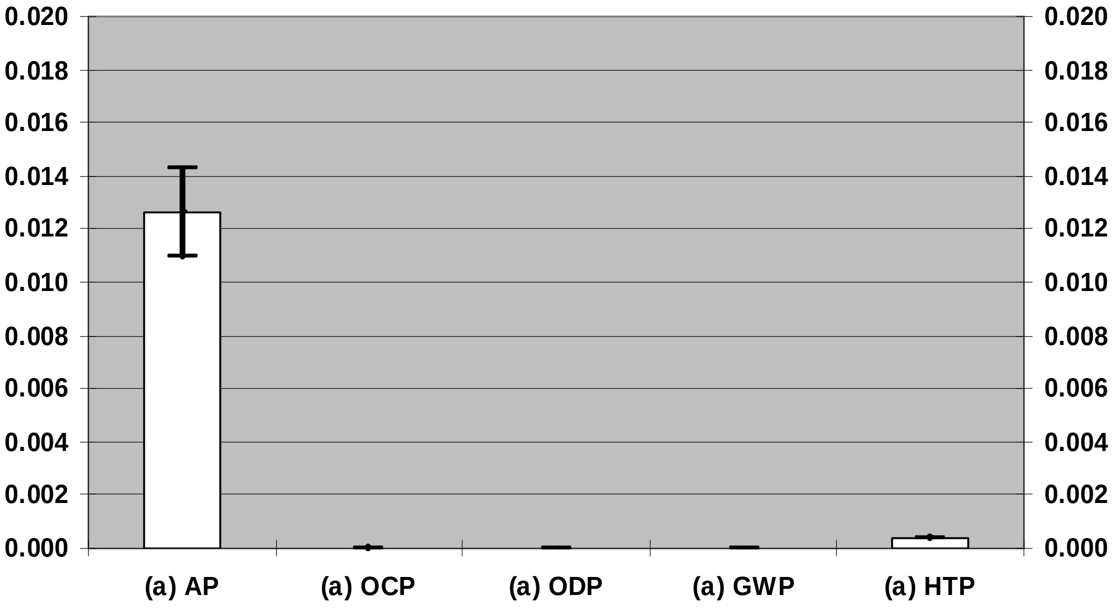


Figure D2: Sensitivity of the air RII profile to electricity usage

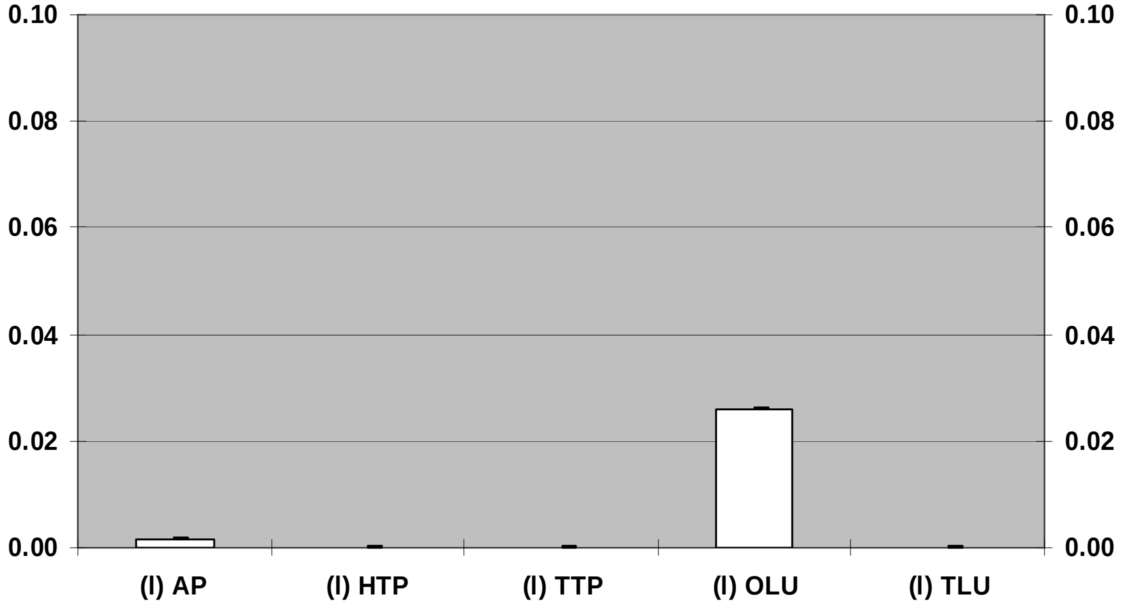


Figure D3: Sensitivity of the land RII profile to electricity usage

Figure D4: Sensitivity of the mined abiotic RII profile to electricity usage

Appendix E: Sensitivity analyses based on the uncertainty of transportation usage of the main unit processes

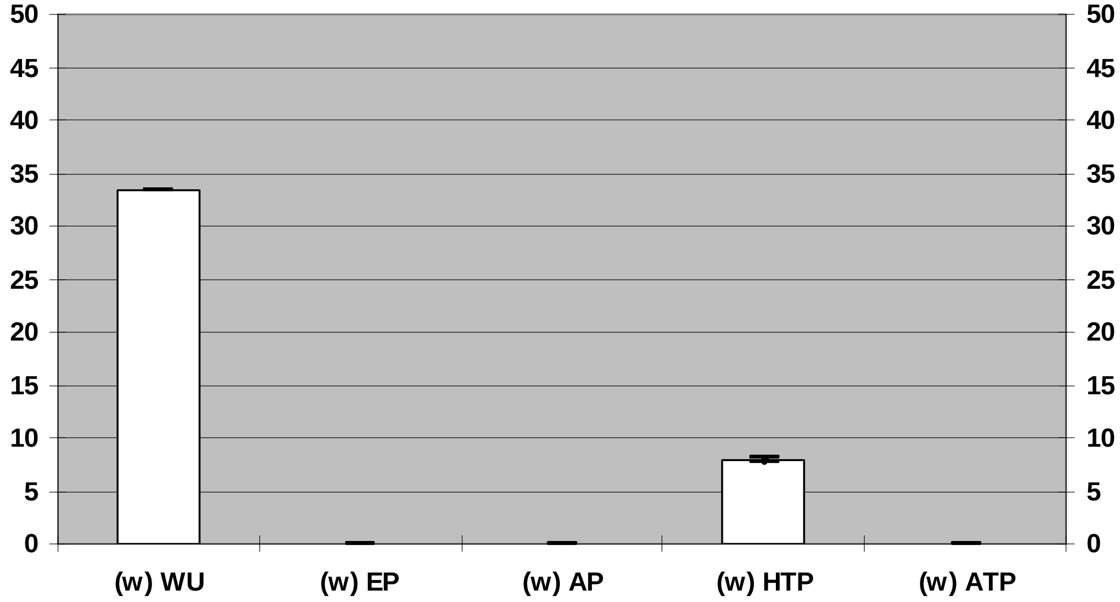


Figure E1: Sensitivity of the water RII profile to transportation

Figure E2: Sensitivity of the air RII profile to transportation usage

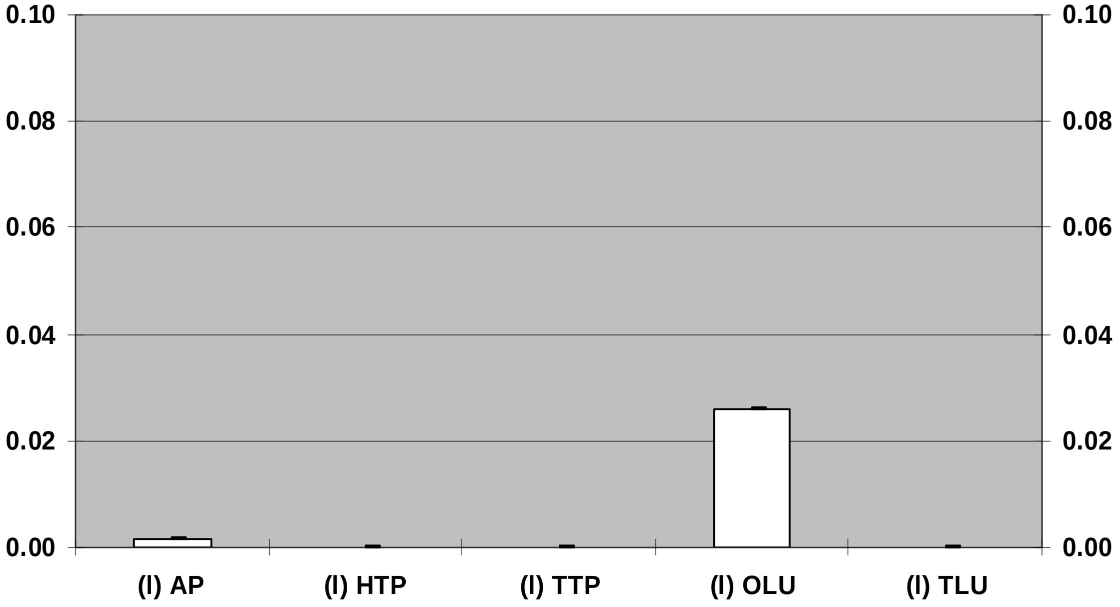


Figure E3: Sensitivity of the mined abiotic RII profile to transportation

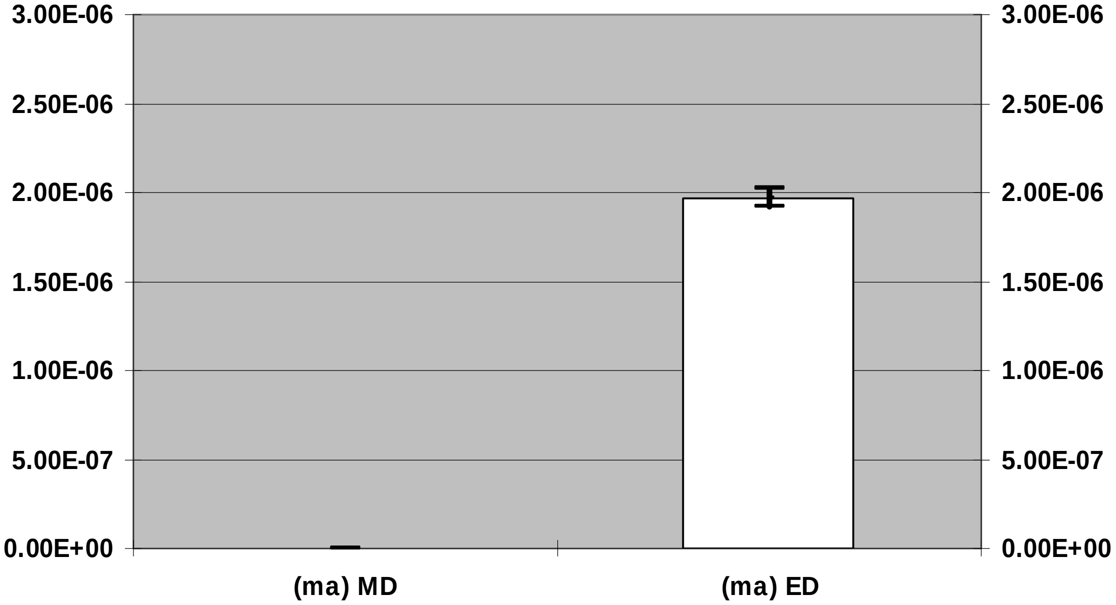


Figure E4: Sensitivity of the mined abiotic RII profile to transportation usage

Appendix F: Sensitivity analyses based on the uncertainty of chemicals usage of the main unit processes

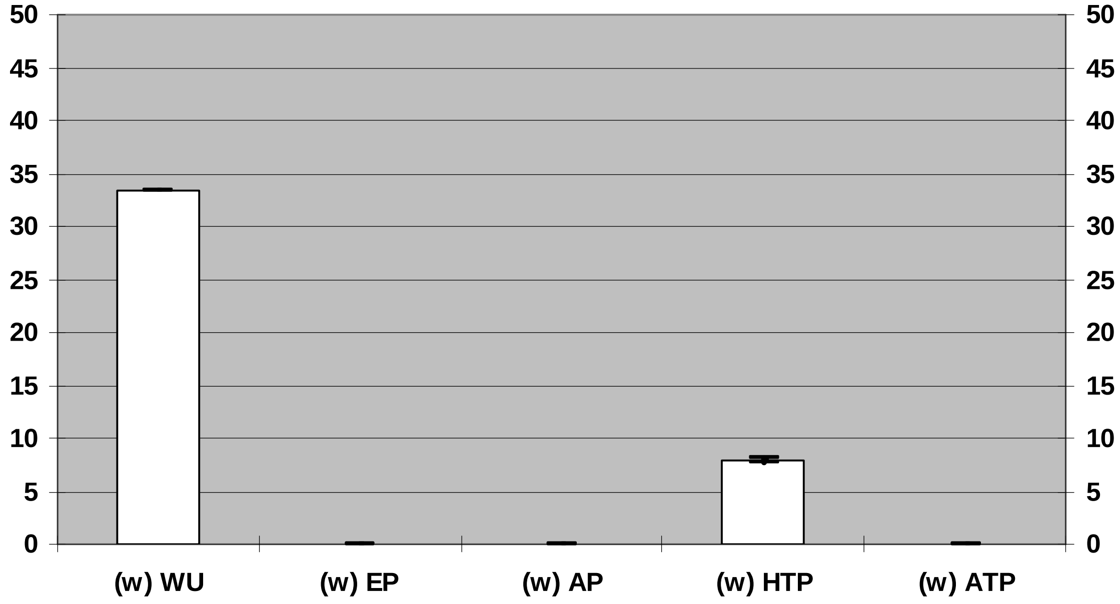


Figure F1: Sensitivity of the water RII profile to chemicals usage

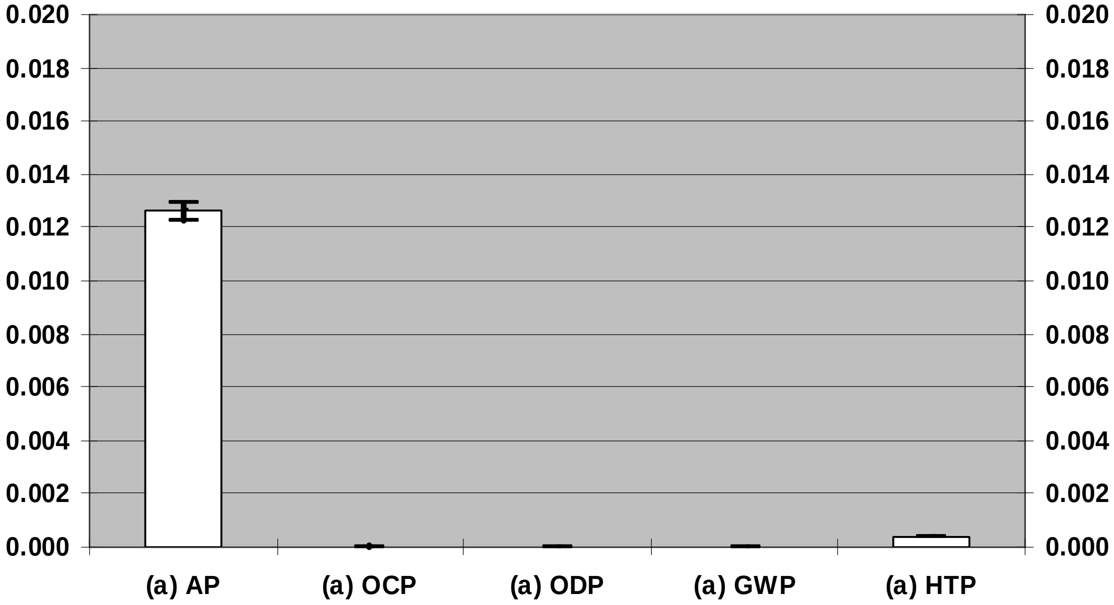


Figure F2: Sensitivity of the air RII profile to chemicals usage

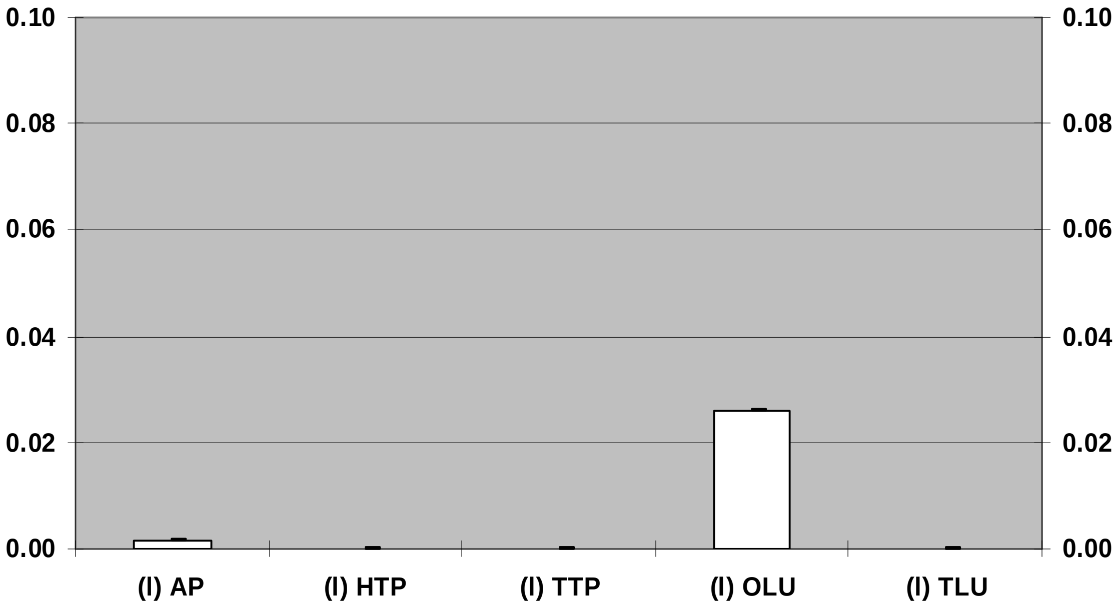


Figure F3: Sensitivity of the mined abiotic RII profile to chemical use

Figure F4: Sensitivity of the mined abiotic RII profile to chemicals usage

Appendix G: Sensitivity analyses based on the uncertainty of land usage of the main unit processes

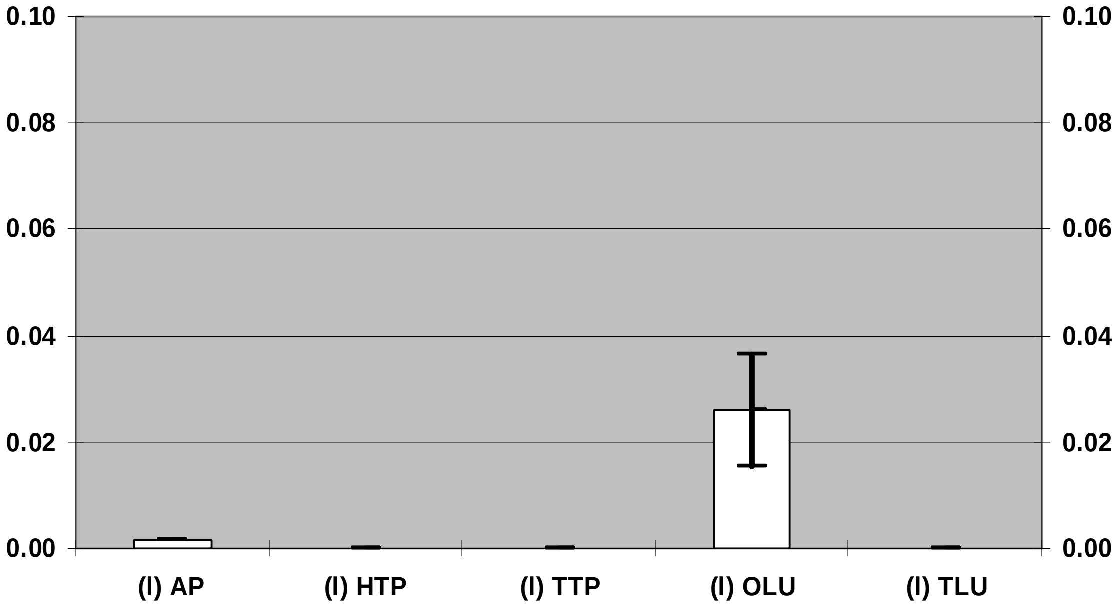


Figure G1: Sensitivity of the land RII profile to land usage

Appendix H: Sensitivity analyses based on the minimum and maximum of sludge treated at Panfontein treatment facility

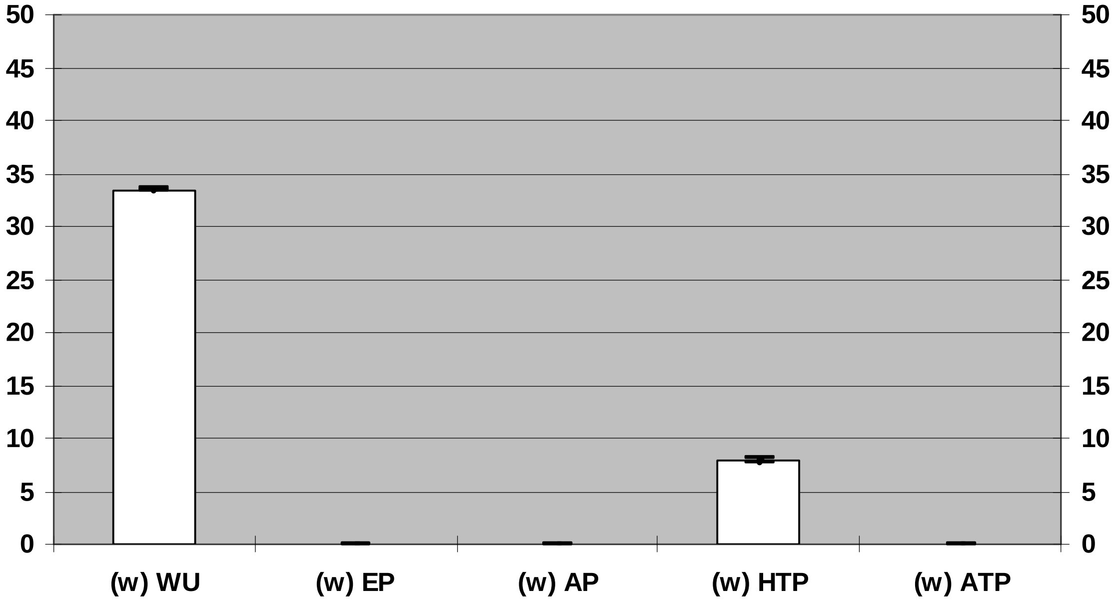


Figure H1: Sensitivity of the water RII profile to the sludge treatment

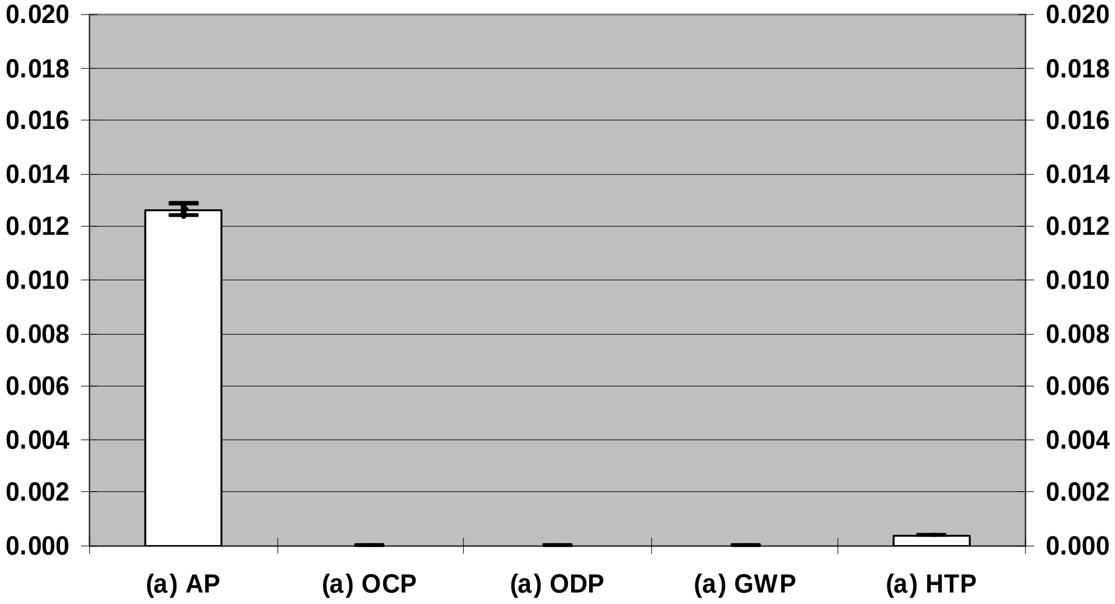


Figure H2: Sensitivity of the air RII profile to the sludge treatment

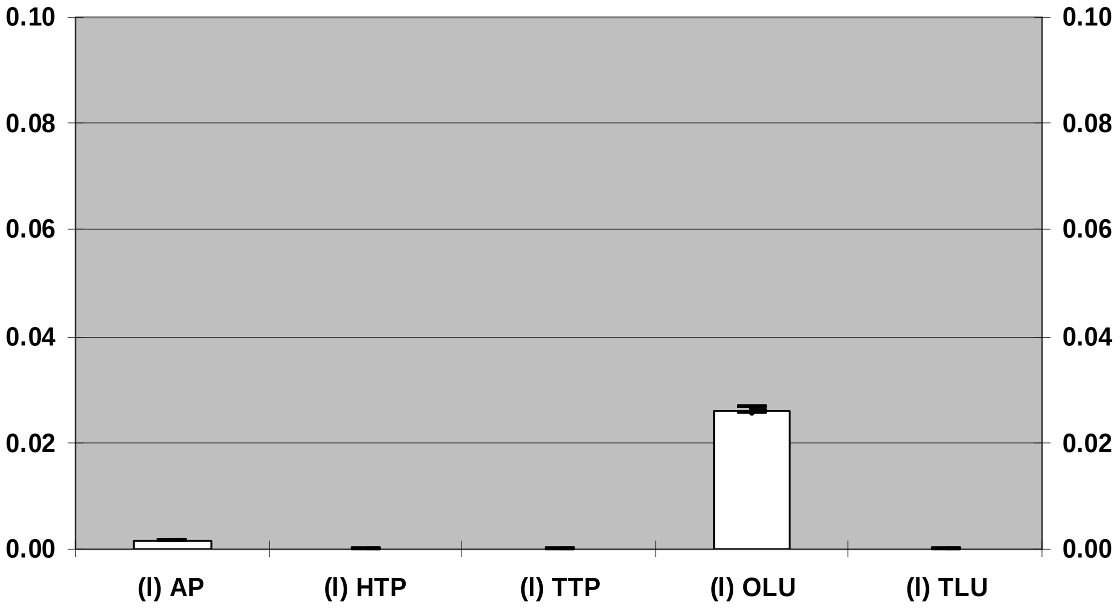


Figure H3: Sensitivity of the land RII profile to the sludge treatment

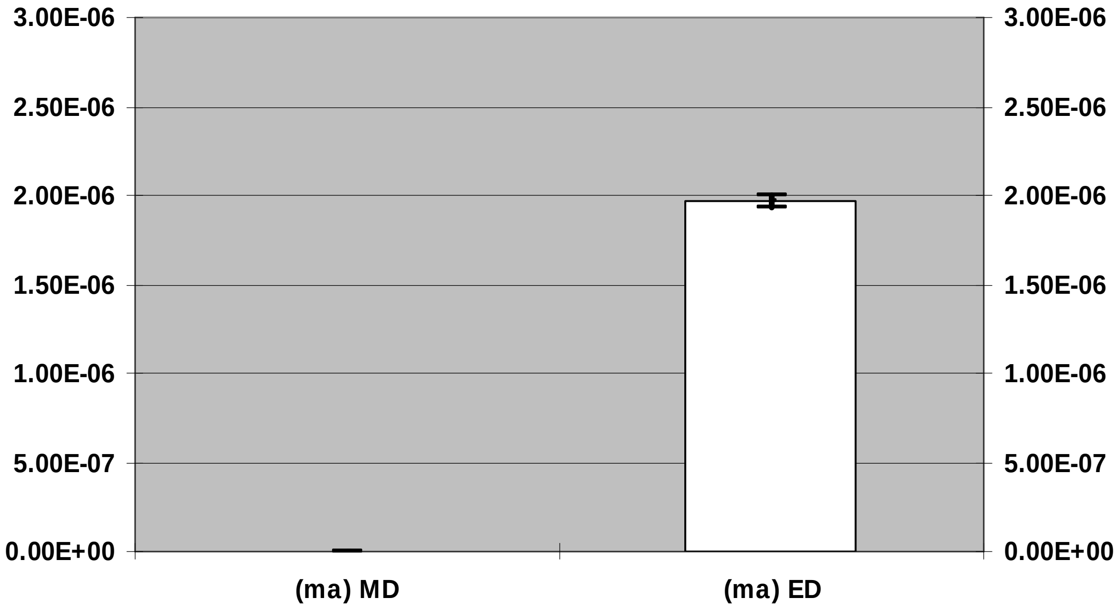


Figure H4: Sensitivity of the mined abiotic RII profile to the sludge treatment