A Life Cycle Analysis for the Application of Decentralised Sanitation Technologies at Newlands Mashu in the eThekwini Municipality

By
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Submitted in fulfilment of the academic requirements of Master of Science in Engineering

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DECLARATION

I,…….., declare that

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ABSTRACT

Safe sanitation is a privilege and in many developing countries sanitation provision is an ongoing major issue. To meet the growing sanitation demands of developed and developing countries around the world, various sanitation technologies and systems have been proposed. One such technology that is highlighted in this study is the Decentralised Wastewater Treatment System (DEWATS). DEWATS is a wastewater treatment technology that aims to treat and dispose of wastewater near the source that the wastewater is generated and excludes the conventional centralised sewer network that directs wastewater to a regional wastewater treatment plant (WWTP). As with all wastewater treatment technologies, various wastewater treatment phases and processes intrinsically impact the environment. It is important for engineers, planners, designers and stakeholders involved in the treatment of wastewater to be informed of the various environmental consequences as a result of the implementation of DEWATS. The purpose of this study was to undertake an environmental Life Cycle Assessment (LCA) of a DEWATS in a local context. The DEWATS plant considered in this study is located in eThekwini Municipality, KwaZulu-Natal and was designed to treat wastewater volumes of 41.6m³/d. This study was aligned with LCA guidelines produced by the International Organisation for Standardisation. During the Life Cycle Inventory (LCI) phase of this study, data for both the construction and operation phases were collected and subsequently processed using SimaPro LCA analysis software and the CML (Centrum Melieukunde Leiden) midpoint methodology. The key findings of this study revealed that domestic water consumption was the largest contributor to environmental impacts on the impact categories considered. Further to this, it was found that low flush interventions resulted in a large reduction in wastewater and significantly improve the environmental profile of the DEWATS. Based on the results of this study it is recommended that further emphasis on the reduction of greywater generation is required and a reduction on the reliance on municipal domestic water. Although a separate process, the minimisation of the energy requirements of upstream water treatment processes may significantly improve the environmental profile of the DEWATS.

ABBREVIATIONS

- ABR - Anaerobic Baffled Reactor
- AF - Anaerobic Filter
- AnMBR - Anaerobic Membrane Bioreactor
- AP - Acidification Potential
- BOD – Biochemical Oxygen Demand
- BORDA – Bremen Overseas Research and Development Association
- CAB - Communal Ablution Block
- CML - Centrum Melieukunde Leiden
- COD – Chemical Oxygen Demand
- DEWATS – Decentralised Wastewater Treatment Systems
- DHS - Department of Human Settlement
- DMs – Decision-Makers
- DSW – Durban Solid Waste
- DWA – Department of Water Affairs
- DWAF - Department of Water Affairs and Forestry
- EIO-LCA - Economic Input-Output Life Cycle Assessment
- EP - Eutrophication Potential
- EWS – eThekwini Water and Sanitation
- FBSan - Free Basic Sanitation
- GHG – Greenhouse Gas
- GWP - Global Warming Potential
- HDPE – High-Density Polyethylene
- HFCW – Horizontal Flow Constructed Wetlands
- ISO - International Standard Organisation
- JMP - Joint Monitoring Programme
- KZN - KwaZulu-Natal
- LCA – Life Cycle Assessment
- LCI – Life Cycle Inventory
- LCIA – Life Cycle Impact Assessment
- LLDPE – Low Linear Density Polyethylene

- LWA - Light Weight Expanded Aggregate Material
- MBR – Membrane Bioreactor
- MDG - Millennium Development Goal
- MIG - Municipal Infrastructure Grant
- MODM - Multiple-objective decision-making
- MRI – Midwestern Research Institute
- NEMA – National Environmental Management Act
- NTS – Natural Treatment System
- ODP - Ozone Depletion Potential
- O&M – Operation and Maintenance
- PGF – Planted Gravel Filter
- PRG – Pollution Research Group
- PVC – Polyvinyl Chloride
- QMRA – Quantitative Microbial Risk Assessment
- RDP – Reconstruction and Development Programme
- REPA – Resource and Environmental Profile Analysis
- SAFE - Sanitation Appropriate for Education
- SALGA - South African Local Government Association
- SETAC – Society of Environmental Toxicology and Chemistry
- SFD - Shit Flow Diagram
- UDDT – Urine Dry Diverting Toilet
- UKZN – University of KwaZulu-Natal
- UNEP – United Nations Environment Programme
- UNICEF – The United Nations International Children's Emergency Fund
- USF – University of South Florida
- VFCW – Vertical Flow Constructed Wetland
- VIP – Ventilated Improved Pit Latrine
- WEC - Wastewater Electrolysis Cell
- WHO – World Health Organisation
- WRC -Water Research Commission
- WSA - Water Service Authority
- WWTP – Wastewater Treatment Plant

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CHAPTER 1: INTRODUCTION

"If you are a researcher, you are trying to figure out what the question is as well as what the answer is." Edward Witten

1.1. Background Importance

The City of Durban in the Province of KwaZulu-Natal, South Africa is part of the eThekwini Municipality. The municipality is responsible for providing water and sanitation services to approximately 3.77 million people (Statistics SA, 2011 & eThekwini Municipality, 2018). The municipal areas are divided into urban and rural sectors which account for 55% and 45% respectively (eThekwini Municipality, 2015). A ubiquitous problem, which the eThekwini Municipality and most municipalities in South Africa face, is providing adequate sanitation solutions to residents on city peripheries outside of the waterborne edge (Asphala and Armitage, 2011).

The peri-urban areas on the fringes of the eThekwini Municipality continue to extend due to rapid urbanization (Patel, 1995). These densely populated informal settlements on the city edge are often located in flood plains and steep land (eThekwini Municipality, 2015). This coupled with the lack of electricity and water infrastructure makes sanitation and wastewater treatment a difficult task (Bair et al., 2015). According to research by the Pollution Research Group in 2016, 26% of wastewater generated in the eThekwini Municipality is unsafely discharged into the environment and is largely as a result of unserved portions of the population (typically informal settlements). Informal settlements in developing countries, which lack water and sewerage infrastructure, tend to use on-site treatment such as septic tanks due to its affordability and low maintenance requirements (Deilami et al., 2017). In recent times, however, new initiatives and technologies have been implemented in order to provide wastewater treatment alternatives under difficult conditions.

Decentralised Wastewater Treatment Systems (DEWATS) are becoming widely recognized by authorities and city managers across the world as an alternative for

providing wastewater treatment in densely populated low-income areas. DEWATS is a low technology, modular wastewater treatment system that aims to provide solutions not only in the technical and engineering realms of sanitation, but also to local economic and social domains (Gutterer et al., 2009). The low technology approach of this system, also referred to as a natural system, is based on the imitation of natural processes that occur in water bodies and soil (Brissaud, 2007). Although DEWATS are usually low maintenance and low technology, there are environmental impacts associated with the construction and operation of these plants (Frances, 2012).

Environmental Life Cycle Assessment (LCA) can be used as a tool to evaluate the potential environmental impact of the DEWATS at any stage of the treatment process. In the field of sanitation and wastewater treatment technologies, a number of studies (See **Section 2.6.5**) have used comparative assessments in order to assist in the decision-making process. LCA considers all aspects of a product or service's life cycle – from resource extraction, to material production through to final disposal (ISO, 2006a). This study uses LCA to quantify the environmental impacts of the Newlands Mashu DEWATS Plant in eThekwini Municipality, KwaZulu-Natal. The DEWATS plant that this study investigates is a pilot plant established through a partnership between the Pollution Research Group (University of KwaZulu-Natal), eThekwini Municipality and Bremen Overseas Research and Development Association (BORDA). The purpose of the pilot project is to establish information regarding the sanitation technologies.

1.2. Research Rationale

LCA is used as a tool to evaluate the potential environmental impacts of a decentralised wastewater treatment system in Newlands, KwaZulu-Natal. Sanitation provision that is aligned with international baseline standards (WHO & UNICEF, 2017) is a major problem in many developing nations around the world. Sanitation has been highlighted as an indispensable constituent towards achieving the United Nations 2030 Sustainable Development Goals (UN, 2015). A number of organisations and institutions have launched initiatives in an attempt to solve the health and sanitation issues experienced in developing countries. BORDA, is an organisation,

established in Germany, that develops novel methods of utilizing renewable energy to improve the livelihood of disadvantaged people in developing nations (Gutterer et al., 2009). BORDA have successfully implemented the design and operation of a number of DEWATS plants in developing nations around the world (BORDA, 2017).

The eThekwini Municipality is in the process of providing sanitation infrastructure to informal communities that lack appropriate sanitation. DEWATS has been highlighted as a potential method of wastewater treatment in informal settlements in the eThekwini Municipality. An informed decision regarding the feasibility of various sanitation technologies is of great importance to authorities and decision-makers. An LCA study of the DEWATS will provide further information regarding the environmental performance of the system and hence assist in the decision making process.

1.3. Research Questions

What are the potential environmental impacts of the Newlands Mashu decentralised wastewater treatment system?

1.4. Aims and Objectives

1.4.1. Aims

- To establish information regarding the environmental performance of the Newlands Mashu (NLM) DEWATS plant.
- To provide recommendations for further improvements to the DEWATS sanitation system.
- To inform sanitation professionals on the potential environmental consequences of decentralised sanitation.

1.4.2. Objectives

- To perform LCAs for a number of scenarios related to the NLM DEWATS.
- To compare the environmental impacts of the investigated scenarios.
- To focus on areas of potential improvements in terms of environmental performance.

1.5. Structure of Dissertation

The structure of this dissertation is summarised in **Figure 1**, and the seven chapters and their contents are presented in this figure.

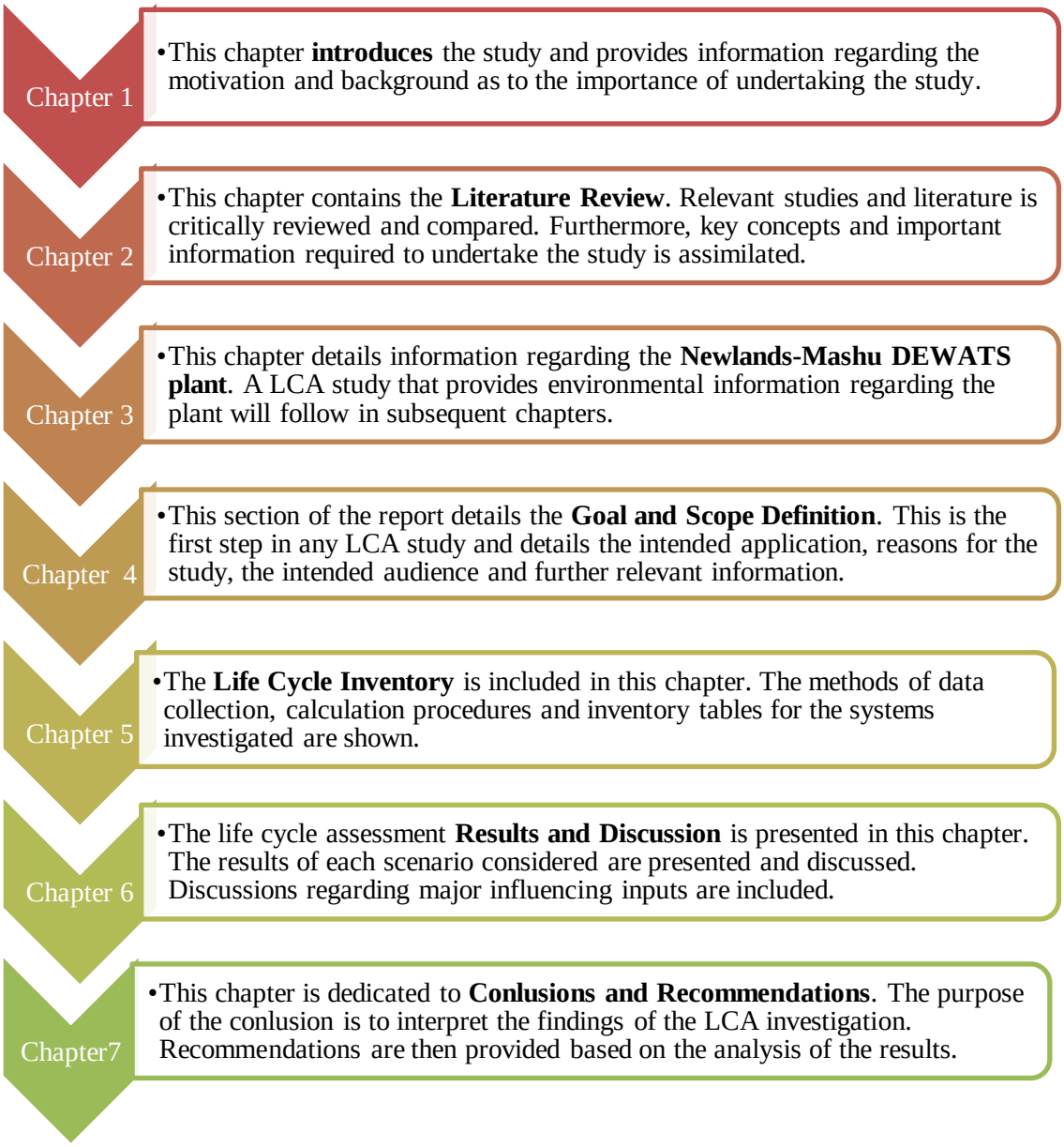

Figure 1: Dissertation Structure

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Literature reviews present the theoretical framework for a study and help investigate the concepts used in relation to the research question. This literature review and study critically evaluates three major topics (shown in **Figure 2** below). Environmental Life Cycle Assessment (LCA), sanitation in developing countries as well as Decentralised Wastewater Treatment Systems (DEWATS). They will be discussed in the literature review that follows.

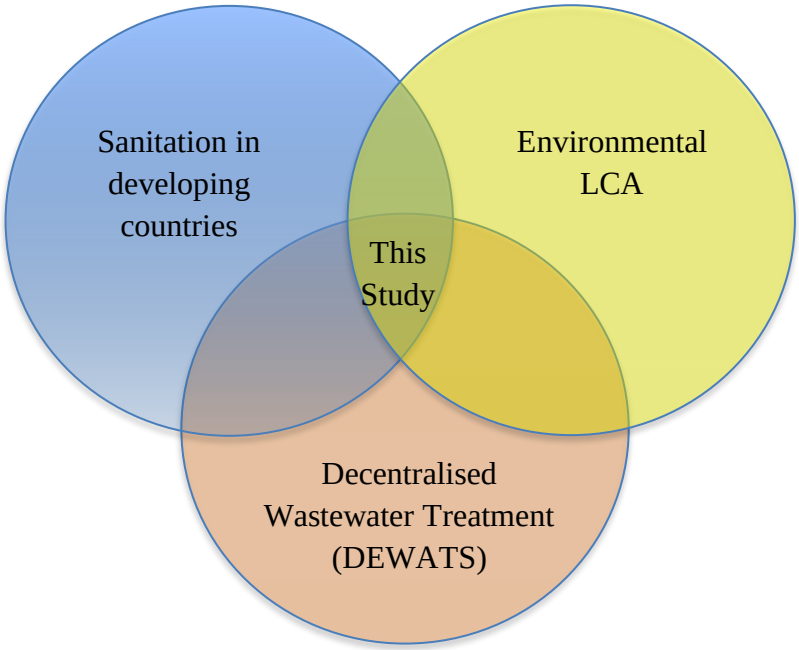

Figure 2: Venn diagram of the main focuses of the study

2.2. Definitions and Importance of Sanitation

Sanitation has been defined by different authors with emphasis on different aspects. According to the World Health Organisation (WHO, 2020), sanitation is defined as "the provision of facilities and services for the safe management of human excreta from the toilet to containment and storage and treatment onsite or conveyance, treatment and eventual safe end use or disposal". In addition to water, sanitation is likely the most essential and crucial service (Perard, 2018). Sanitation is undeniably important to humanity in a number of valuable ways. According to the Joint Monitoring Programme

(JMP) for Water Supply and Sanitation compiled by WHO and UNICEF (in 2008, the International Year of Sanitation) the five key messages of sanitation include:

- Sanitation is vital for human health
- Sanitation generates economic benefits
- Sanitation contributes to dignity and social development
- Sanitation helps the environment
- Sanitation is achievable

In the sub-sections that follow, these key messages will be further explained.

2.2.1. Sanitation and Human Health

An abundance of research has demonstrated the impact that water, sanitation and hygiene interventions have on human health. The impact of sanitation on health is threefold, consisting of direct impact due to infections, conditions caused by preceding infection and lastly broader well-being.

Unfortunately, in many developing countries, open defecation remains the norm as data suggests that approximately 2.5 billion people are without access to improved sanitation facilities (WHO and JMP, 2008). Due to the poor provision of adequate water and sanitation, millions of people suffer from preventable illnesses and die each year (WHO & UNICEF, 2004). As previously mentioned, the use of unsafe sanitation systems may result in infection and disease, including:

- Diarrhoea, which is typically a symptom of gastrointestinal infection, causes approximately 1.65 million deaths per year globally and accounts for approximately 20% of under-five deaths in South Africa (Chola et al., 2015).
- Schistomiasis and soil-transmitted helminths are tropical diseases that cause significant morbidity worldwide, and more particularly in sub-Saharan Africa (Bronzan et al., 2018).
- Vector born diseases due to poor sanitation practices in low- and middle-income countries in tropical and subtropical regions (Degroote et al., 2018).

Improved Sanitation

It is both relevant and important to define improved sanitation as per the World Health Organisation standards. Improved Sanitation can be described as facilities that safeguard human contact from human excreta through hygienic separation (WHO and JMP, 2008). Improved sanitation facilities include:

- Flush or pour-flush toilet/latrine to:
    - Piped sewer system
    - Septic tank
    - Pit latrine
- Ventilated improved pit latrine
- Pit latrine with slab
- Composting toilet

Figure 3 on the right illustrates the Four-step ladder to improved sanitation. A step down the ladder indicates an improvement in sanitation. Not having access to at least shared or improved sanitation may compromise public health as well as economic development (Acey et al., 2019).

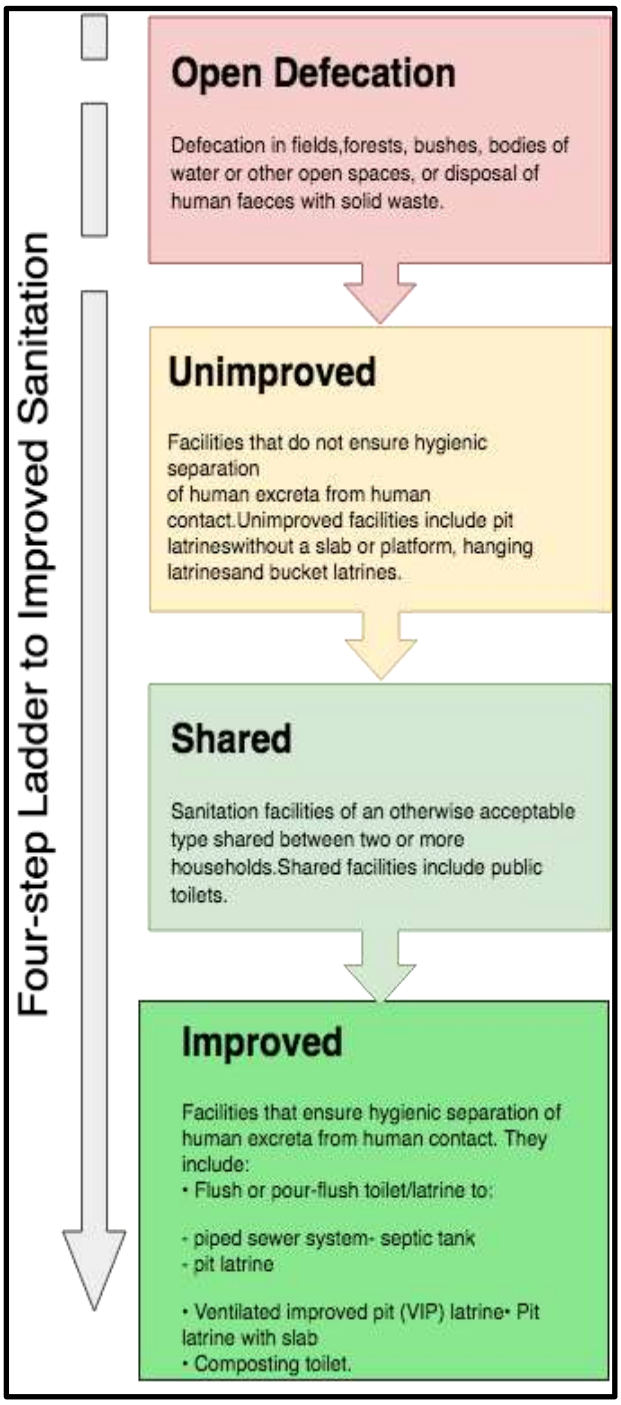

Figure 3: UNICEF & WHO Four-Step Ladder to Improved Sanitation (UNICEF, 2008)

2.2.2. Sanitation and Economic Impacts

Drinking water supply and sanitation are both able to generate significant economic returns to society (Hutton, 2015). Limited access to improved sanitation is estimated to have a serious impact on the economy of developing countries. A survey consisting of 18 African countries showed that the annual economic losses due to unsafe sanitation are estimated to be between 1% and 2.5% of GDP. Investing in sanitation results in four broad economic benefits (Hutton, 2012):

Savings from reducing the amount of healthcare visits for diarrhoeal disease.

1. Savings as a result of reduced productive time losses from disease (many working days are lost due to diarrhoeal disease).
2. Savings due to a reduction in premature mortality.
3. Closer proximity to improved sanitation results in time savings and hence also increased productivity time.
4.

The investment required to achieve universal access to improved sanitation is about 0.10% of low and middle-income countries' total GDP. Achieving universal sanitation is, therefore, more realistic than once thought. The main obstacle in providing universal sanitation lies with low willingness to pay (Perard, 2018). Overall it is clear that the provision of improved sanitation results in significant economic benefits and is affordable to implement on a global scale, however, the unwillingness to pay for shared benefits is the main hurdle in providing universal sanitation.

2.2.3. Sanitation and the Impacts on Mental and Social Well-Being

The influence of the lack of access to improved sanitation on mental and social well-being has been investigated in a number of studies (Bisung and Elliott, 2016, Caruso et al., 2018, Khanna and Das, 2016, Sclar et al., 2018). As discussed previously, the link between inadequate sanitation and physical health consequences (illness and disease) is undeniable. However, if we are to look at health from a holistic perspective as defined by WHO (2020) as a "state of complete physical, mental and social well-being", then it is important to also include the latter two health dimensions.

Some mental and social well-being benefits of having access to improved sanitation listed by Cairncross (2018) include 'comfort, convenience, privacy, security, social status and aesthetic benefits". An individual may not notice health improvements or a reduction in the frequency of illness when gaining access to improved sanitation, since they may lack the knowledge of how certain diseases are transmitted. However, with regard to the social and mental well-being benefits of improved sanitation it becomes clearly apparent, after practicing open defecation in the dark, they are able to practice within the bounds of a private and secure cubicle. Thus, the benefits of improved sanitation on social and mental well-being can be broadly summarised as upholding one's dignity and may be more apparent to the user than health benefits.

2.2.4. Sanitation and the Environment

Sanitation is an incessant human requirement and has a direct impact on the environment. Both conventional sanitation ubiquitous in developed countries and less sophisticated sanitation practices pervasive in developing countries each have an impact on the environment. In recent times there has been a paradigm shift in the way people perceive development and its impact on the environment. When aiming to solve current sanitation issues, "sustainable development" is a term that will always be at the forefront of discussion. "Sustainable development" emerged out of the Brundtland report in 1987 and is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Major cities in developed countries rely on conventional wastewater treatment methods (piped sewage reticulation and wastewater treatment plants). These conventional methods are increasingly thought to be unsustainable. Contrarily, in the urban and peri-urban regions in developing countries, a major part of the population rely on onsite sanitation facilities such as pit latrines that have the potential to cause groundwater contamination (Graham and Polizzotto 2013).

Conventional wastewater treatment in developed countries, as mentioned earlier, rely on piped sewer systems which direct wastewater to a centralised wastewater treatment plant (WTP). A significant quantity of potable drinking water is used to aid in the conveyance of particulate matter in the sewer. Wastewater which is received at centralised WTP thereafter undergoes various biological, mechanical, and

physiochemical processes in order to eradicate organic matter and nutrients before finally being discharged to surface waters. The processes involved in the water-wastewater cycle (distribution, pumping, treatment) account for a considerable amount of global energy consumption. For example, the energy consumption of the water-wastewater cycle accounts for approximately 1% in Sweden, 3% in the United States of America and United Kingdom of the total energy consumption in their respective countries (Meyers, 2012). Due to electricity requirements, the operational phase of conventional wastewater treatment plants were found to result in the most significant environmental burden (Emmerson et al., 1995, Shao et al., 2014). Conventional municipal wastewater treatment processes produce greenhouse gases (methane and carbon dioxide) from the breakdown of excreta (Czepiel et al., 1993).

Large water consumption is a major drawback of conventional wastewater treatment methods. It has been shown that at endpoint level, water deprivation impacts on ecosystem quality and on resource damage categories are substantial for wastewater treatment technologies with significant water use in water-scarce regions (Risch et al., 2014). Conventional wastewater treatment technologies collect wastewater as a single mixed source that is contaminated with faecal pathogens. The recycling potential is largely reduced and potentially useful wastewater constituents such as wastewater and nutrients are often wasted (Wilderer, 2004).

It is not only conventional sanitation practices and technologies that have a harmful impact on the environment. Approximately 2.5 billion people worldwide do not have access to improved sanitation (WHO and JMP, 2008), approximately 1.77 billion people worldwide use pit latrines (Graham and Polizzotto 2013) and approximately 1.1 billion people practice open defecation (WHO, 2010). Since pit latrines lack a physical barrier beneath the ground this has shown to result in the contamination of groundwater sources which are in close proximity (Graham and Polizzotto 2013).

Unimproved onsite sanitation technologies used in densely populated regions pollute the environment with extremely high nutrient loads (Fourie and Ryneveld 1993). Eutrophication is the process whereby a body of water becomes enriched in dissolved nutrients – such as nitrogen and phosphorous – that result in the rapid growth of aquatic plant life and depletion of dissolved oxygen (Peavy et al., 1985). The depletion of

dissolved oxygen has the potential to harmfully impact aquatic life. Unimproved sanitation has the potential to degrade surface water and groundwater sources that has a direct impact on the biological diversity of aquatic ecosystems (Peavy et al., 1985). In conclusion, the conventional means of wastewater treatment may be a safe means of disposing of excreta, however, this system has come under scrutiny in recent times due to its large energy and water requirements. Moreover, unsafe sanitation practices trigger both health and environmental consequences

2.3. Sanitation in South Africa

It would be remiss to not mention South Africa's past when discussing the current sanitation situation in South Africa. After the abolishment of the Apartheid regime in 1994, the new democratic government began the task of addressing large disparities inherited from the Apartheid Government. The rural black population were most often without access to adequate sanitation, whereas the affluent urban white minority were served with both potable water supply and centralised piped sewage treatment and disposal. During this transition period, it was estimated that approximately 21 million South African's (half of the population) were without access to adequate sanitation (DWAF, 2004).

In the Apartheid system, there did not exist a department whose sole responsibility was to provide water supply and sanitation services. At that time it was decided by the local municipality and homeland government whose responsibility this was to be (DWAF, 2004). This system changed when the national program for the provision of sanitation services was established along with the Reconstruction and Development Programme (RDP) (DWAF, 1994). The current governance system and further details regarding sanitation in South Africa are discussed in the subsections that follow.

2.3.1. Water and Sanitation Governance in South Africa

Water and sanitation is a deeply political issue in South Africa. Large sanitation backlogs in informal settlements in South African communities have often resulted in the increase in service delivery protests (Morudu, 2017, Tapela, 2015). For this reason, political parties often use the lack of adequate sanitation in these areas as a major electioneering point.

The provision of sanitation is the responsibility of the local government departments, which comprises of the Housing Department, the Health Department and the Department of Water and Sanitation (DWAF, 2005). A summary overview of the institutions involved in both water supply and wastewater treatment, taken from the Department of Water Affairs and Forestry (DWAF), can be found in Appendix A. The local government is referred to as the Water Services Authority (WSA). In terms of water supply to consumers, the WSA is responsible for ensuring that water supply infrastructure is developed, operated and maintained. Furthermore, the WSA (municipality) bares the responsibility of the collection and treatment of sewage, wastewater and effluent. In South Africa, a WSA can be either a Category A (Metropolitan), Category B (Local) or Category C (District) municipality. The WSA is afforded the decision of performing the functions of a water services provider itself or it may enter into a contract with another water services provider (DWAF, 2005). The WSA is required to produce an annual interim water services development plan (WSDP) that aids authorities to make informed decisions with regard to water and sanitation services. The WSDP is also particularly important in planning for providing services to communities, which lack basic services in its area of jurisdiction and forms part of the Integrated Development Plan (IDP) process (DWAF, 2005).

The provincial and national government bares the constitutional responsibility to support and strengthen the capacity of local government in the fulfilment of its functions, and to regulate local government to ensure effective performance of its duties (DWAF, 2003). The Department of Water Affairs (DWA) – previously the Department of Water Affairs and Forestry – is the custodian of South Africa's water resources and of the National Water Act and the Water Services Act (Tissington, 2011). DWA's role in water and sanitation is the formulation of policy governing the sector. Both the South African Constitution (section 155(7)) as well as the Water Services Act (section 62(1)) allows DWA the mandate to monitor the performance of all water service institutions, including local government who perform the function of WSAs. In 2009, the National Sanitation Programme Unit was reassigned from DWA to the Department of Human Settlement (DHS). This arrangement allocated the responsibility of household sanitation infrastructure to DHS and bulk reticulation to DWA (Tissington, 2011). Since there is a direct relationship between public health and sanitation, the Department of Health is an

important role player in sustainable health and hygiene education in South Africa. Finally, the role of National Treasury with regard to sanitation is to provide funding to various departments and spheres of government (Tissington, 2011).

2.3.2. Sanitation Policy in South Africa

The related acts, policies, strategies and guidelines as outlined by the DWS's National Sanitation Policy of 2016 are listed in **Appendix B.** The new democratic government of 1994 in South Africa faced the difficult task of addressing large water and sanitation backlogs in predominantly black informal settlements. During this time, the national program for sanitation provision in South Africa as well as the Reconstruction Development Programme (RDP) was established. "Meeting the Basic Needs" was one of the four pillars of the RDP and hence, water supply and sanitation for all South African citizens was prioritized.

2.3.3. Sanitation Service Levels and Backlogs in South Africa

In discussing sanitation levels and backlogs, it is important to note that sanitation backlogs do not only consist of the provision of sanitation services. It is, therefore, relevant to understand the various types of sanitation backlogs experienced in South Africa. **Table 3** taken from the DWA 's 2012 *Report on the Status of Sanitation Services in South Africa* outlines and describes the types of sanitation backlogs experienced.

Table 1: Types of Sanitation Backlogs in South Africa (Department of Water Affairs, 2012)

Sanitation Backlog	Description
Service Delivery backlog	Backlogs of people who have never been served
Refurbishment backlog	Sanitation infrastructure that has deteriorated beyond typical maintenance requirements
Extension backlog	Existing infrastructure that needs to be extended to provide the service to new households in the communities
Upgrade needs	Infrastructure that does not meet the minimum requirements

Operation and maintenance (O&M) backlogs	Infrastructure that has not been adequately operated and maintained, but can be adequate if funds are allocated to ensure proper operation and maintenance

In **Appendix C** there are two pie charts attached, which are also taken from DWA (2012). From these charts, a number of observations are made regarding sanitation backlogs in South Africa in 2012. Approximately 11% (both informal and formal without services) still require the provision of sanitation services. Moreover, according to the DWA, at least 26% of households within formal areas have access to sanitation services that do not meet required standards due to the deterioration of infrastructure caused by "a lack of technical capacity to ensure effective operation, timely maintenance, refurbishment and/or upgrading, pit emptying services and/or insufficient water resources".

Data released by Statistics South Africa in 2017 has shown that 63.3% of households in South Africa used flush toilets which discharge to either a public sewerage system or septic tank system (Statistics SA, 2017b). A further 12.2% had access to a pit latrine with a ventilation pipe and a minor 0.3% used Ecological toilet technologies (including urine diversion toilets). The aforementioned sanitation technologies are classified as improved sanitation and hence a collective 75.8% of households have access to improved sanitation. A large number of households are still without access to improved sanitation as can be observed from the 13.7% of households that make use of pit latrines without a ventilation pipe, 2.2% make use of a bucket system, and 2.4% are without access to sanitation.

Despite many households not having access to adequate sanitation, **Table 2** demonstrates how access to improved sanitation has increased between 2011 and 2016. Access to flush toilet systems connected to public sewerage has increased by 3.6% and the percentage of households using a pit latrine with a ventilation pipe has increased by 3.4%. The use of technologies that are deemed to be unimproved have decreased. The use of pit latrines without a ventilation pipe has decreased by 5.6% and the percentage of households without access to any sanitation has decreased by 2.8% (Statistics SA, 2017b).

Table 2: Household access to sanitation in South Africa, 2011 and 2016 (Statistics SA, 2017)

	2011	2016	Change
Flush toilet connected to public sewerage system	57.0	60.6	3.6
Flush toilet connected to septic tank system	3.1	2.7	-0.4
Chemical toilet (including ecological sanitation)	2.5	4.5	2.0
Pit latrine with ventilation pipe	8.8	12.2	3.4
Pit latrine without ventilation pipe	19.3	13.7	-5.6
Bucket toilet	2.1	2.2	0.0
Other	2.1	1.6	-0.5
None	5.2	2.4	-2.8

Beyond the difficulty of physically providing households with access to improved sanitation, there also exists social and legal issues which impact the progress of development. Since most informal settlements occur on private land, providing basic services to people living on land without permission of the owner poses a significant challenge to WSAs (DWAF, 2003).

2.3.4. Service Provision Targets

The South African government has made substantial progress in respect to addressing both water supply and sanitation backlogs since the abolishment of Apartheid. The initial sanitation backlog was 52% in 1994 (DWAF, 2004) and has since advanced with an increase in overall access to adequate sanitation to 79.9% in 2015 (Statistics SA, 2017b). The 2015 Millennium Development Goal (MDG) of halving the proportion of the population without access to sustainable access to sanitation was achieved in 2008 (Department of Water Affairs, 2012). However, substantial improvements are required to meet further goals including the Medium-term Strategic Framework 2014-2019 (MTSF) Goals and the Sustainable Development Goals (SDGs) for 2030.

There are a number of short and long-term goals, which the South African Government has committed to achieving. The MTSF is the South African Government's strategic plan for the 2014-2019 electoral term and lays out the actions the Government will take and the targets that need to be achieved. The MTSF 2014-2019 goal with regard to sanitation is to increase household access to functional sanitation service from 84% in 2013 to 90% by 2019 as well as elimination of the bucket sanitation system in formal areas (Department of Planning Monitoring and Evaluation, 2014).

The future of water and sanitation in South Africa is guided by a number of various short and long-term targets. South Africa has committed to both internal goals that are aligned with international and continental programmes that aim to achieve universal improved sanitation.

2.4. Sanitation Systems

A Sanitation System (Tilley et al., 2014) is a series of technologies and services for the management of "wastes" or "products". The "products" travel through a series of functional groups that consist of technologies that may be selected to suit the requirements of a particular context. Furthermore, a sanitation system also consists of the management, operation and maintenance required for the continuous safe and sustainable functioning of the system.

2.4.1. Product Materials

Product materials, otherwise known as "wastes" or "resources", are the materials that are introduced into the sanitation system at various phases in the system. Certain products are generated directly from humans (faeces and urine), whilst other products are produced from technologies (flushwater) and some are produced as a result of storage or treatment (sludge) (Tilley et al., 2014). The literature (Tilley et al., 2014) lists twenty products that are typical of various sanitation systems. In terms of products which are introduced at the user interface of a sanitation system, **Figure 4** shows the definition of these products and includes excreta, brownwater and blackwater.

- Excreta contain urine and faeces that is not mixed with any flushwater.

- Brownwater consists of a mixture of faeces and flushwater but does not contain urine. Brownwater may also consist of anal cleansing water and dry cleansing material, depending on which is preferred by the user.
- Blackwater consists of a mixture of urine, faeces and flushwater along with anal cleansing water and/or dry cleansing materials.

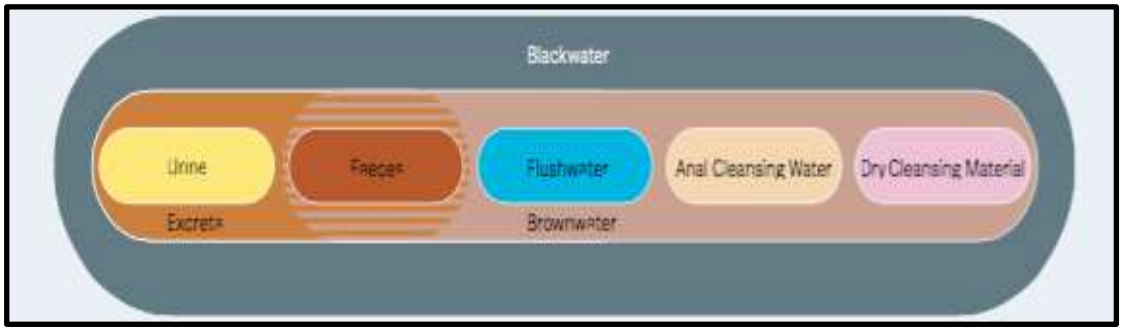

Figure 4: Definition of Excreta, Brownwater and Blackwater (Tilley et al., 2014)

2.4.2. System Functional Groups

A functional group is defined as a group of technologies that perform a similar function. There are five separate functional groups wherein technologies can be selected to construct a sanitation system (Tilley et al., 2014). The five functional groups are listed and described as:

- User Interface describes the toilet structure (toilet, pedestal, pan) with which the user comes into contact. The user interfaces included in the literature (Tilley et al., 2014) consists of the dry toilet, urine dry diverting toilet (UDDT), urinal, pour flush toilet, cistern toilet and the urine diverting flush toilet.
- Collection and Storage/Treatment refers to the technologies that collect and store waste generated at the user interface. A number of these technologies are designed to treat the products, whereas others are designed for storage and collection purposes.
- Conveyance describes the technologies which are used to transport products that are generated at either the user interface or collection and storage/treatment technology to a (semi-) centralised treatment technology or a use and/or disposal technology.
- (Semi-) Centralised Treatment refers to technologies which are typically more suited to large user groups (neighbourhoods and cities). The operation,

maintenance and energy requirements of this functional group are usually higher than smaller scale technologies.

- Use and/or Disposal describes the means in which products are ultimately returned to the environment, either as a useful resource or reduced-risk materials.

2.4.3. Sanitation System Templates

A system template, as defined by the literature (Tilley et al., 2014), consists of a number of compatible and demonstrated technology combinations that can be selected for a given application. The system templates are used to compare a number of different technologies which are suitable for a certain application and which take into account product flow from the user interface to use or disposal (Tilley et al., 2014). Nine system templates as listed in **Table 3**, can be selected for an application. A number of novel technologies that are not listed will be mentioned in following sections.

Table 3: List of System Templates

System No.	System Description
1	Single Pit System
2	Waterless Pit System without Sludge Production
3	Pour Flush Pit System without Sludge Production
4	Waterless System with Urine Diversion
5	Biogas System
6	Blackwater Treatment System with Infiltration
7	Blackwater Treatment System with Effluent Transport
8	Blackwater Transport to (Semi-) Centralised Treatment System
9	Sewerage system with Urine Diversion

2.4.4. Sanitation Systems in South Africa

Since South Africa is a developing country in which a large portion of the population is without improved sanitation facilities, it would make sense to divide South African Sanitation Systems into “Improved” and “Unimproved” sanitation technologies. The definition of an improved sanitation facility was previously described in Figure 4

(UNICEF and WHO four-step ladder to improved sanitation) and refers to facilities which ensure the hygienic separation of excreta from human contact (WHO and JMP, 2008). The following systems (both improved and unimproved) - mentioned in the passages that follow - summarised from the listed sanitation systems in Statistics South Africa's report on the state of basic service delivery in South Africa (Statistics SA, 2017b).

i) Improved Sanitation Systems

Flush toilet connected to public sewerage system: this particular system typically appears in one of two templates, depending on what user interface is selected for the system. In a system that uses a typical cistern flush toilet, blackwater will be conveyed in a single product stream via a piped public sewerage system. If a Urine-Diverting Flush Toilet (UDFT) is selected, urine and faeces are collected in separate streams and hence the brownwater is, thereafter, conveyed via a piped public sewerage system. Often referred to as the "conventional" sanitation system, this system has come under scrutiny in recent times with regard to its large energy consumption requirements (due to conveyance and treatment). There are a number of issues regarding the application of the conventional sanitation system in certain applications. In high-density informal settlements, a lack of reliable basic services such as water supply and electricity and a lack of urban planning reduce the feasibility of this system. In sporadic rural communities, the conventional system is unfeasible due to energy requirements and costs of conveying wastewater over large distances (Thibodeau et al., 2014).

Flush toilet connected to a septic tank system: similar to the previous system, the user interface of the system may be selected to suit the application and requirements of the system. The waste product stream is conveyed via pipe and plumbing fixtures to an underground watertight settling chamber with a liquids outlet to a subsoil drainage system. In this system the septic tank is typically used for a pre-treatment and storage and thereafter transported to a (semi-) centralised treatment facility and, thereafter, used or disposed (Tilley et al., 2014).

Ventilated Improved Pit Latrine (VIP): the VIP consists of a pit; cover slab, well-ventilated top structure and private cubicle. As seen in Figure 5, the pit and cover slab forms the sub structure and the private cubicle and ventilation pipe form the

superstructure. Depending on the stability of local soil conditions the pit may be lined or unlined. The pit may need top be elevated above ground level depending on the water table level. VIPs are suitable for water-scarce and less densely populated regions (UNICEF, 2015). Operation and maintenance is typically the responsibility of the local authority and often requires mechanical pit emptying, sludge transfer, treatment and disposal. The organic material in the pit decomposes with time and is usually emptied every five years (Tissington, 2011).

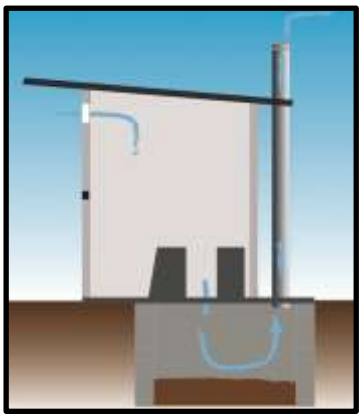

Figure 5: Typical section through VIP (UNICEF, 2015)

Composting toilet: a composting toilet consists of two primary components: the toilet and the tank. Other common components of a composting toilet include a fan and vent pipe to remove any odour (Anand and Apul, 2014). Composting systems use minimal or no water for the conveyance of the waste product. The waste that is collected in the composting tank undergoes aerobic digestion. Oftentimes additional bulking agents are added assist in the management of various types of waste, adjust carbon to nitrogen ratio and increase the porosity of the compost (Anand and Apul, 2014).

Ecological toilets: ecological sanitation is a broad term used for a number of different sanitation systems that aim to prevent disease and promote health, protect the environment and conserve water, recover and recycle nutrients and organic matter (Esrey and Andersson, 2001). Otherwise known as Eco-San, ecological sanitation is based on the closure of material flow cycles to recover resources and reduce the demand on other resources. Hu et al., (2016) provides an in-depth review of the Eco-San system including the various alternatives for user interface, collection and conveyance, storage and primary treatment and reuse or disposal (Hu et al., 2016).

ii) Unimproved Sanitation Systems

Open defecation: open defecation is the worst form of sanitation practice and is at the bottom of the four-step ladder to improved sanitation (WHO & UNICEF, 2017). Open defecation involves disposing of human waste (faeces and urine) in garbage bins, water bodies, public areas, forests, farmlands and other open spaces (UNICEF and WHO, 2015). Open defecation has severe ramifications: it causes infant fatalities, affects the physical and cognitive development of surviving children, poses a significant threat to the environment and jeopardises safety, privacy and dignity (Abubakar, 2018). Those who do not have access to improved sanitation facilities primarily practice open defecation. However, it has been demonstrated that merely having access to improved sanitation facilities does not always change sanitation preferences and some would rather resort to open defecation (Coffey et al., 2014). Promoting the use of improved sanitation facilities is necessary to change the behaviour. Open defecation occurs in both rural and urban areas, however, it is more prevalent in rural areas.

Public or Shared Latrine (used by more than one household): as described in the JMP's four-step ladder to improved sanitation, shared sanitation is "sanitation facilities of an otherwise acceptable type shared between two or more households" (WHO and JMP, 2008). Shared sanitation has been confirmed as the only viable and appropriate sanitation solution for densely populated, unplanned slums (Schouten and Mathenge, 2010).

Simple Pit latrine (without ventilation pipe or slab): simple pit latrines provide the most basic form of sanitation in many informal settlements. The simple pit latrine consists of an excavated pit in the ground that is covered with wooden branches and soil, and a squathole for the disposal of faeces. The user is required to stand on exposed soil around the squathole when defecating into the pit. Simple pit latrines are classified as unimproved by the JMP, however, little evidence has been put forth to confirm this classification. Baker and Ensink (2011) undertook a study in order to analyse the presence of helminth eggs in the soil surrounding the squathole of 72 simple latrines in a village in Tanzania. It was found that 71% of collected samples tested positive for helminth eggs. The study proved that the absence of a cleanable covering slab deems this particular sanitation system unimproved since this system is unable to effectively separate faecal matter from human contact (Baker and Ensink, 2012).

Chemical Toilet: a chemical toilet collects human excreta and uses a chemical mixture to reduce odours. The waste products contained in the holding tank are emptied periodically and transported to a wastewater treatment plant for treatment and disposal. This sanitation system is typically a self-contained and movable structure. Depending on the specific unit, some systems make use of a flushing mechanism and others are dry systems. Chemical toilet systems are temporary sanitation solutions and are ideal for construction sites, large gathering events such as sports events and outdoor concerts. This particular system is also particularly suited to emergency situations to provide sanitation for a given period of time until a suitable permanent solution has been decided on (CSIR, 2000).

Bucket Systems: a bucket system consists of a pedestal with a pan or bucket placed beneath as a means of collecting human excreta. The user defecates into the bucket and once the bucket is full it is manually emptied. Decomposition is typically minor and secondary treatment is required (Stenström et al., 2011). Urine, faeces and dry cleansing material are typically the products that enter the system. Anal cleansing water is discouraged since this will cause the bucket too fill up too soon.

2.4.5. The Shift from Central Systems to Household Technologies

Both unimproved sanitation and improved sanitation solutions ubiquitous to most countries have come under scrutiny over the last few decades. The “drop and store” type unimproved pit latrines, for example, are unable to effectively protect humans from the transmission of helminths (Baker and Ensink, 2012) and have the potential to pollute groundwater (Graham and Polizzotto 2013). The “flush and forget” type centralised wastewater treatment facilities use vast amounts of precious water to convey a small volume of urine and faeces, reduce resource recovery potential and the costly nature of this resource dependent system is unaffordable in developing countries. Most importantly, the aforementioned conventional sanitation systems impair nature’s natural nutrient cycle and soil fertility. Figure 6 demonstrates the one way flow of nutrients in conventional sanitation systems which leads to the pollution of water bodies, reduction of water supply and loss of fertility of soil (Lamichhane, 2007).

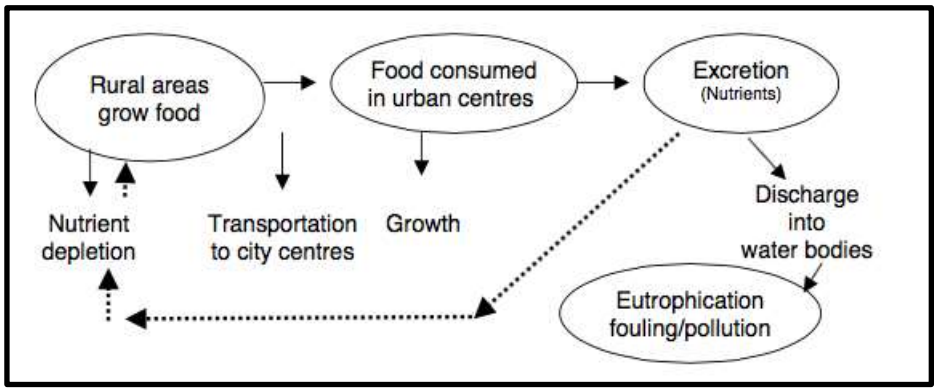

Figure 6: Linear flow of nutrients (Lamichhane, 2007)

Both "drop and store" and "flush and forget" types of sanitation systems are based on the premise that human excreta is a waste product that needs to be disposed of. A paradigm shift in the way that sanitation systems should manage human excreta is required. Untreated human excreta contain organic matter, plant nutrients, trace elements and micronutrients as well as pathogens, viruses, helminths, endocrine substances and medical residues. When poorly managed, they have the potential to cause major health and environmental harm, however, if managed effectively they are able to have a beneficial impact to local resources (Esrey and Andersson, 2001).

Contrary to the "end-of-pipe" conventional sanitation systems, ecological sanitation (EcoSan) attempts to "close the loop" and relies on ecologically and environmentally sound management of resources (nutrients, energy and water) (Otterpohl, 2002). EcoSan refers to various technologies that uphold the principles of ecological sanitation and are outlined in a number of publications (Esrey and Andersson, 2001, Hu et al., 2016, Langergraber and Muellegger, 2005, Otterpohl, 2002). The three fundamental principles of ecological sanitation include: pollution prevention, sanitizing urine and faeces and safely reusing products for agriculture (Winblad and Simpson-Hebert, 2004).

A large portion of the population, mostly residing in informal settlements and slums, are without access to improved sanitation (approximately 2.5 billion) (WHO, 2010). Conventional "flush and forget" type of sanitation systems is typically unaffordable and inappropriate for the aforementioned population. EcoSan technologies have shown to be comparatively more affordable (to poor people) and would be a suitable alternative (Lamichhane, 2007). However, it is important to note that in the future, a paradigm shift in sanitation systems used in more affluent communities will also be required. The

unsustainable use of valuable resources by affluent communities due to conventional sanitation is also a major concern. As put by Sunita Narain at the 2nd international Symposium on Ecological Sanitation: "We have to remember that it is the rich person's flush that is the biggest environmental culprit today

2.5. DEWATS

A brief overview of Decentralised Wastewater Treatment Systems (DEWATS) is covered in Section 2.5.1 of this dissertation. This section aims to provide the reader with further information regarding the design, performance and operation of DEWATS from selected studies (Gutterer et al., 2009, Tayler, 2018).

2.5.1. Overview of DEWATS

The sustainability of conventional wastewater treatment systems has come into question under various applications around the world. In developing countries and in particular peri-urban and rural communities, centralised wastewater treatment is often unfeasible when compared with decentralised wastewater treatment (Massoud et al., 2009). Morever, in developed countries, centralised treatment systems have been shown to be uncapable of coping with strict environmental legislation (Schories, 2008). As a result, various decentralised wastewater treatment options have been explored (Beausejour and Nguyen, 2007, Boano et al., 2020, Fane and Fane, 2005, Singh et al., 2015). DEWATS can be classified into various categories based on the method treatment and technology used. The classification of these systems is outlined in the literature (Singh et al., 2015). In the passages that follow, a brief summary of the systems is provided including natural treatment systems, aerobic systems, anaerobic systems and combined systems.

i) Natural Systems

Natural treatment systems (NTSs) are grounded on naturally occurring processes that make use of attenuation and buffering capacity of natural soil-aquifers and plant-root systems (Singh et al., 2015). The removal of contaminants from the influent wastewater is not facilitated by the use of substantial amounts of energy or the use of chemicals. Natural systems are generally used in places where large space is available and funds are limited. NTSs incur low operation and maintenance costs and require less energy compared with conventional primary and secondary treatment alternatives (Arceivala

and Asolekar, 2006). NTSs can be further classified into soil-based and aquatic treatment systems. An overview of NTSs can be found in the literature (Singh et al., 2015).

ii) Aerobic Systems

Aerobic treatment is a process in which microorganisms make use of oxygen in order to decomposition organic material into final stabilised products as shown in **Figure 7** (Peavy et al., 1985). Moreover, aerobic systems can also be distinguished as the systems that often require forced aeration or mechanical equipment (Singh et al., 2015). Aerobic systems can be further broken into three separate categories including suspended growth, attached growth and combined suspended and attached growth systems (Singh et al., 2009). When compared with NTSs, the footprint of the aerobic system is much smaller. The aerobic system requires considerably more energy, but the aerobic systems are often able to achieve effluent discharge standards (Singh et al., 2009).

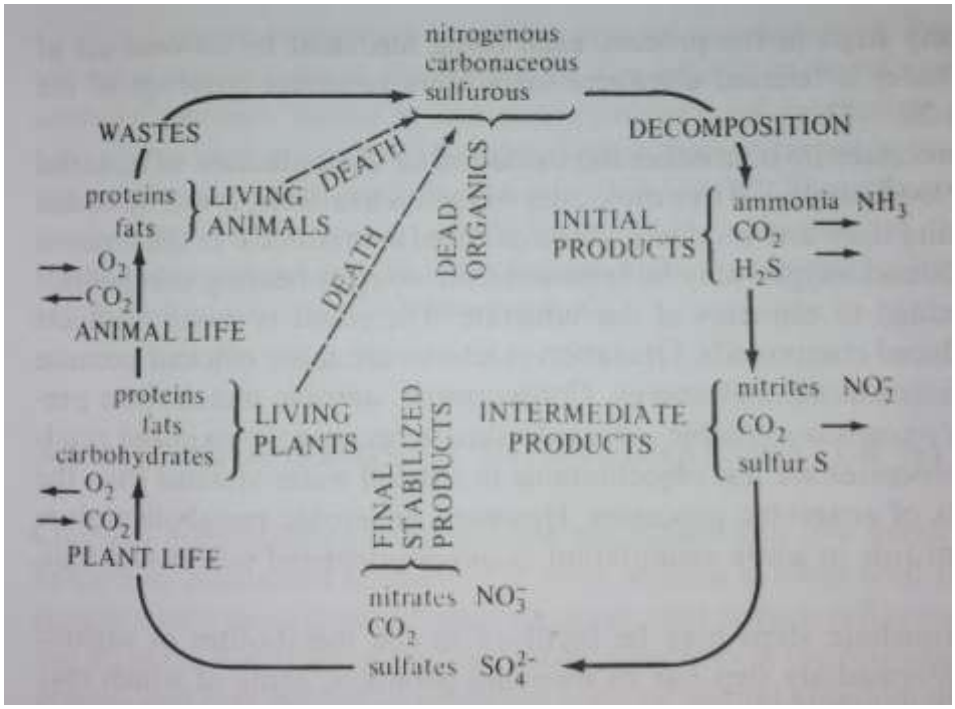

Figure 7: Nitrogen, carbon, and sulphur cycles in aerobic processes (Peavy et al., 1985).

iii) Anaerobic Systems

Anaerobic treatment processes involve the conversion of organic materials into methane, a product that can be potentially result in net energy gain from process operations (McCarty and Smith, 1986). The nitrogen, carbon, and sulphur cycle in

anaerobic processes, shown in **Figure 8**, demonstrates the fact that anaerobic processes occur in the absence of oxygen (Peavy et al., 1985). Anaerobic systems typically accomplish poor to moderate effluent quality and require an extensive period of time to start up when compared with aerobic systems (Alexiou and Mara, 2003, Melidis et al., 2009). In order to meet discharge standards, anaerobic systems are usually followed by aerobic systems (Chan et al., 2009).

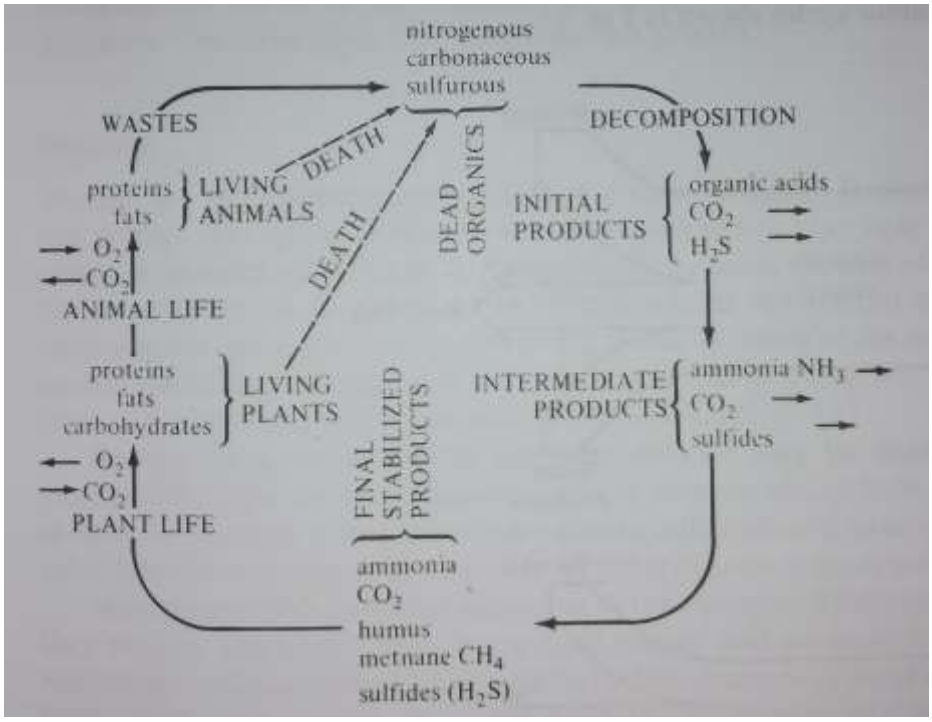

Figure 8: Nitrogen, carbon, and sulphur cycles in anaerobic processes (Peavy et al., 1985)

iv) Combined Systems

Combined systems components from all three natural, anaerobic and aerobic treatment systems. These systems combine a number of technical components such as the Imhoff tank, septic tank, anaerobic filer, baffled septic tank, trickling filter, hybrid and some natural systems (Singh et al., 2015).

2.5.2. DEWATS and Developing Countries

There are a number of issues with use of conventional centralised wastewater treatment in developing countries. Centralised wastewater collection and treatment systems are sometimes not the most environmentally friendly or financially viable option (e.g. wastewater treatment facilities often require expensive mechanical components and electricity to operate the machinery). Conventional wastewater treatment plants are

synonymous with sophisticated technology also requiring operation by skilled personnel. Conventional wastewater treatment is often unfeasible in areas with low populations and sporadic households (U.S. EPA, 2002). The infrastructure required for conventional sanitation is inflexible and expensive due to high capital costs. Alternative solutions are often more appropriate in certain contexts in developing nations.

Where the sustainability of conventional sanitation has been scrutinized (Wilderer, 2005), the DEWATS aims to treat human excreta as a potential resource as well as treating the wastewater close to the point of generation. In the context of developing countries whereby there is shortage of skilled and responsible operation and maintenance, DEWATS is certainly a preferred option (Gutterer et al., 2009).

2.5.3. System Description

i) Primary Treatment

Primary treatment at a typical DEWATS system uses either a biogas digester or a settler. In the primary treatment phase, sedimentation occurs as easily settleable solids are removed from the wastewater and settle in the component. Dome-shaped biogas digesters (see **Figure 9**) are often used as a settling step in BORDA DEWATS plants. The option of a biogas digester is particularly favourable with concentrated wastewater streams. The half-sphere shape is constructed with bricks and is integrated into the ground. The influent wastewater is separated into liquid and solid phase as sedimentation occurs and organic solids undergo biological digestion. If the concentration and quantity of wastewater is sufficient enough, biogas can be harvested and used for cooking, heating or light.

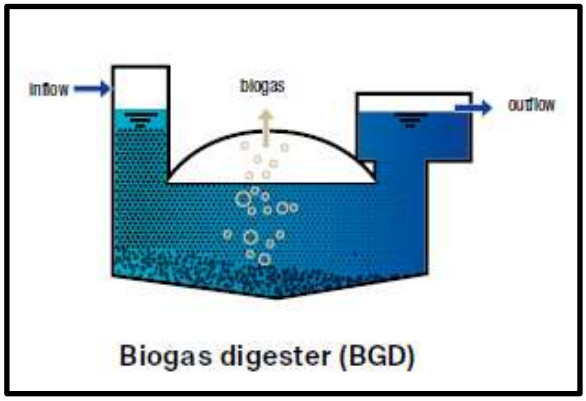

Figure 9: Typical Biogas Digester Unit (BORDA, 2017)

ii) Secondary Treatment

Secondary treatment at DEWATS are normally provided by an anaerobic baffled reactor unit. Anaerobic baffled reactors (ABRs) are a series of consecutive tanks separated by baffles (See **Figure 10**). ABR tanks are typically constructed of masonry brick, reinforced concrete or prefabricated fiberglass. In an ABR unit, anaerobic heterotrophic bacteria utilize organics in the absence of oxygen. This biochemical metabolic process and the organisms involved are the means in which wastewater is treated in the ABR unit. The ABR unit removes dead organics through anaerobic digestion and settling of suspended material. As shown in **Figure 10**, baffles or pipes are used to direct wastewater to an opening slightly below the surface water level to the bottom of the subsequent compartment. In the process, the wastewater is brought into direct contact with a layer of settled sludge and provides an opportunity for organisms to metabolize the organic pollutants.

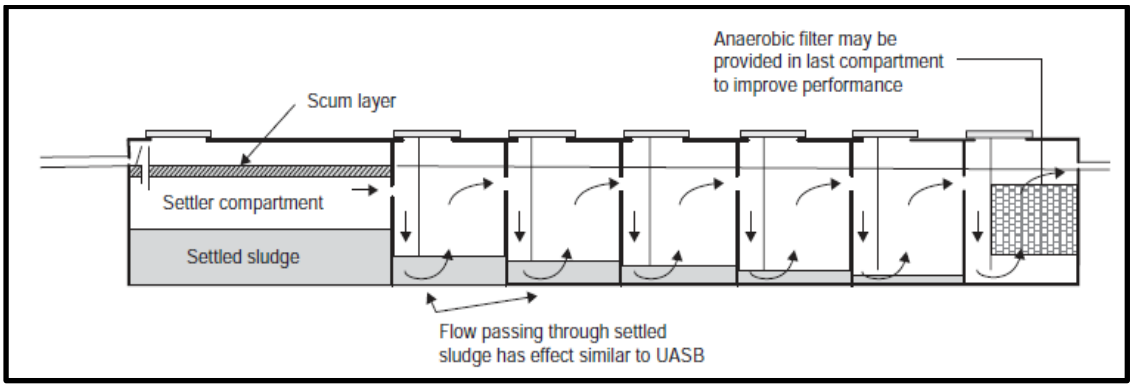

Figure 10: Typical ABR unit with initial settling compartment and subsequent anaerobic filter (Gutterer et al., 2009)

ABRs typically include a settling compartment followed by between four to six upflow partitions and finally one or more anaerobic filter chambers. The settling compartment provides for initial settling of large solids before subsequent upflow compartments. In some occasions, the settling unit is attached to the upflow compartments and if initial settling has been provided, preceding treatment processes may be excluded entirely.

As shown in **Figure 10**, it is common practice to include one or more anaerobic filter partitions as a final polishing step. An anaerobic filter (AF) is a common feature of typical BORDA DEWATS plants. The AF is suited to domestic wastewater that has a low content of suspended solids. In terms of the processes at work, the AF combines solids-removal with digestion of dissolved organic material (BORDA, 2017). The AF provides filter surfaces for biological activity and increases the contact time between fresh wastewater and active microorganisms. The flow of wastewater through the AF is similar to the ABR since wastewater flows upstream through a series of pipes embedded in the chamber walls (BORDA, 2017).

iii) Secondary Aerobic/Facultative Treatment

Facultative treatment involves treating wastewater with a low suspended solids content that requires subsequent nutrient removal in an attempt to meet relevant discharge standards. Further to nutrient removal, tertiary treatment is also used for pathogen removal. Planted Gravel Filters (PGF) are the typical option used for this treatment step (BORDA, 2017).

Horizontal or Vertical Flow Constructed Wetland are typically used in this phase of treatment. Horizontal Flow Constructed Wetlands (HFCW) rely on biological conversion, physical filtration and chemical adsorption to remove nutrients and treat the wastewater. The bottom slope of the HFCW is typically 1% with a horizontal flow direction. The horizontal filter is permanently soaked with water and functions partially aerobic, partially anoxic and partially anaerobic. According to BORDA, the expected BOD reduction rate is between 75-90% and pathogen removal is expected to be over 95% (BORDA, 2017).

A Vertical Flow Constructed Wetland (VFCW) consists of a planted filter bed that is drained at the bottom of the bed. Wastewater from the AF typically flows to an

intermittent dosing chamber preceding the VFCW. The wastewater is then dosed intermittently through parallel pipes on top of the VFCW. The intermittent dosing of the VFCW is achieved through a dosing device installed inside the chamber. In order to equally distribute the wastewater throughout the VFCW, holes are drilled into the pipes (BORDA, 2017).

2.5.4. Technical Performance

Pilot scale studies and laboratories have been established in order to understand the performance of DEWATS. Many of which report COD removal rates of greater than 80 per cent (Tayler, 2018). Since this study aims to establish environmental information regarding a specific (Newlands Mashu DEWATS) DEWATS, and performance may vary from system to system, the performance of the Newlands Mashu (NLM) DEWATS system in KwaZulu-Natal will mainly be emphasized and compared with published literature.

i) COD Removal

Pillay et al. (2014) provided a comprehensive report regarding the performance of the NLM DEWATS. Information regarding influent Chemical Oxygen Demand (COD) concentrations and the final effluent COD concentrations (after polishing step in constructed wetlands) from this work is summarised in **Table 4.** From the table, it is clear that the DEWATS system has the capability to achieve almost 90% COD removal. The anaerobic baffled reactor unit alone is capable of reducing COD to less than the South African discharge limits for agriculture (400 mg/l). The ABR unit was able to reduce COD to a satisfactory concentration (near agricultural discharge limit) in Research Phase 3 even when all wastewater was diverted into a single ABR stream. Moreover, the NLM DEWATS ABR unit recorded a COD removal efficiency of between 53.2% and 74.2% (Pillay et al., 2014). The lowest removal efficiency (53.2%) was recorded during Research Phase 3, as expected, since the entire hydraulic loading was diverted to a single train in the ABR unit. The highest recorded efficiency was recorded during *Research Phase 1*.

Table 4: Summary of COD removal after final polishing in constructed wetlands at Newlands Mashu DEWATS (Pillay et al., 2014)

Research Phase	Unit	Influent COD	Effluent COD - Wetlands	Removal Efficiency	Notes
1	mg/l	873 ± 279	91 ± 17	89.6%	All streams used, VFCW polishing step
2	mg/l	873 ± 279	117 ± 18	86.6%	All streams used, VFCW polishing step
3	mg/l	873 ± 279	na	-	Single train used only, VFCW failed under loading at three times its capacity
4	mg/l	873 ± 279	190 ± 58	78.2%	All streams used, HFCW polishing step

Singh et al. (2009) evaluated the performance of a DEWATS in Nepal. This particular DEWATS treated wastewater from 80 households and an average daily flow of 10 m^3/d. Interestingly, the NLM DEWATS treats wastewater from 84 households and an average daily flow of 35.9 m^3/d. With regard to COD removal, the DEWATS in Nepal (Singh et al., 2009), the ABR unit was able to achieve up to 77% COD removal. Moreover, the entire DEWATS system was able to achieve a COD removal efficiency of 89.1%. However, when comparing the final effluent concentrations, the NLM DEWATS performed better than the Nepal DEWATS. Another pilot study undertaken in Vietnam (Nguyen et al., 2006) compared the performance of a typical septic tank and an ABR combined with an AF and vertical flow constructed wetlands. The system in Vietnam that treated wastewater in community-based system was able to achieve a COD removal efficiency of 88% and final discharge concentrations of 34.8mg/l (two-step VFCW) (Nguyen et al., 2006).

ii) Nutrient Removal

In terms of nutrients, NH4-N and PO4-P concentrations were measured in all four phases of the research project K5/2002. There are no specified South African guidelines for the discharge of PO4-P for agricultural purposes and hence, this has been neglected from **Table 5**. From **Table 5**, it is clear that Newlands Mashu performs poorly regarding nutrient removal. In only Research Phase 3 the concentration of NH4-N is within the discharge limit for agricultural purposes. The relatively poor performance of this particular DEWATS plant, when compared with other BORDA DEWATS plants, is

thought to be attributed to the combination of low sludge activity and high hydraulic loadings during from stormwater intrusions (Pillay et al., 2014).

Table 5: Summary of nitrogen removal over the various Research Phases at Newlands Mashu DEWATS (Pillay et al., 2014)

Research Phase	Unit	Influent NH_4-N	Effluent NH_4-N - Wetlands	SA Guidelines 1996
1	mg/l	39 ± 16	42 ± 5	<30
2	mg/l	39 ± 16	26 ± 9	<30
3	mg/l	39 ± 16	Na	<30
4	mg/l	39 ± 16	40 ± 15	<30

When compared with the nutrient removal efficiencies of other selected studies, the NLM performs poorly. The community based scenario in Vietnam (Nguyen et al., 2006) including an ABR unit with a subsequent two-step vertical flow constructed wetland was able to achieve a final concentration of 1.8mg/l for NH4-N and removal efficiency of 96%. Separately the study based in Nepal (Singh et al., 2009) was able to achieve a final NH4-N concentration of 45mg/l and removal efficiency of 68%.

2.6. Life Cycle Assessment

2.6.1. What is Life Cycle Assessment?

According to ISO 14040, an LCA is defined as the "compilation and evaluation of the inputs and outputs and potential environmental impacts of a product system throughout its life cycle". Therefore, an LCA is a tool for quantifying the environmental impacts of a particular product/s at all stages in the life cycle of product including "raw material acquisition through production, use, end-of-life treatment, recycling and final disposal"(ISO, 2006a, ISO, 2006b). The entire collective system, which is comprised of unit processes involved in the life cycle of a product, is called the "product system"(Guinée, 2002). LCAs have been applied not only for products but also for services and other systems.

2.6.2. A Brief History of LCA

The development of the present-day LCA has its origins dating back to the 1960s and 1970s in the midst of increasing public concern and awareness of environmental issues

(resource and energy efficiency, pollution control, solid waste) (Klöpffer and Grahl, 2014). These early LCAs were not yet standardised and were initiated under various names such as the resource and environmental profile analysis (REPA), ecobalance, integral environmental analyses and environmental profiles (UNEP, 2011).

One of the initial pioneering studies, which was undertaken by the Midwest Research Institute (MRI), quantified the resource requirements, emission loadings, and waste flows of different beverage containers for the Coca Cola Company in 1969. A further study was also undertaken by the MRI in 1974 for the United States Environmental Protection Agency as well as a study by Basler & Hofman in Switzerland (Guinée et al.,

2011). The studies undertaken by the MRI and others in North America at the time went by the name REPA. In the year 1972, in the United Kingdom, Ian Boustead was performing a study of a similar inventory approach. Boustead performed calculations on the total energy used in the production of numerous types of beverage containers such as glass, plastic, aluminium and steel. This particular study and others undertaken in Europe at the time went by the name 'ecobalance' (Jensen et al., 1998). Between 1970 and 1990, LCAs were performed with a number of varying methods and lacked a prevalent theoretical framework. During this period, there was an apparent absence of collaboration and scientific discussion regarding the structure for LCAs.

The lack of scientific discussion and collaboration came to an end in 1990 when the SETAC (Society of Environmental Toxicology and Chemistry) workshop, 'A Technical Framework for Life Cycle Assessments', held in Vermont would become the birthplace of the initial framework of LCA (Klöpffer and Grahl, 2014). The initial framework (see **Figure 11**) would be known as the 'SETAC triangle' and consisted of three components, namely Inventory, Impact Analysis and Improvement Analysis (Fava et al., 1991). The year 1993 saw a further modification to the existing 'SETAC triangle' at the Sesimbra (Portugal) workshop. The new structure would consist of four components, including Goal Definition and Scoping, Inventory Analysis, Impact Assessment and Improvement Analysis (Klöpffer, 2014). This period of convergence through the efforts and coordination of SETAC is referred to as 'harmonisation of LCA by SETAC' (Klöpffer, 2014) and would thereafter be followed by standardisation. The International Standard Organisation (ISO) produced the first international standard in

1997 (ISO 14040) and a slightly modified international standard (see structure in **Figure 12**) in 2006 (ISO 2006a). Since the release of the accepted ISO 14040 series, a rapidly expanding number of LCA studies have been produced (Guinée et al., 2011, UNEP, 2011).

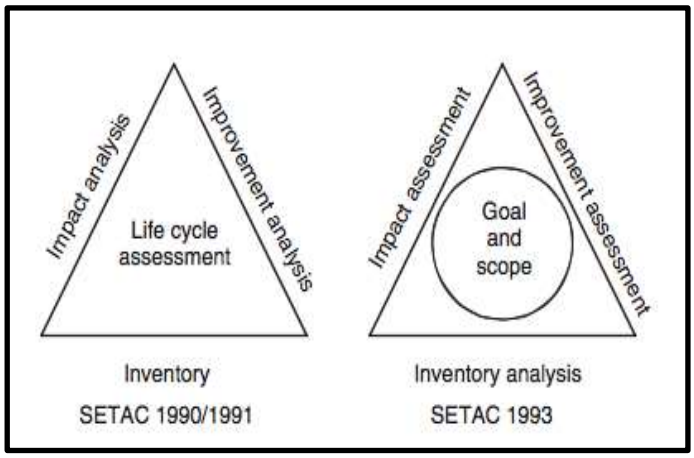

Figure 11: 'SETAC Triangle'

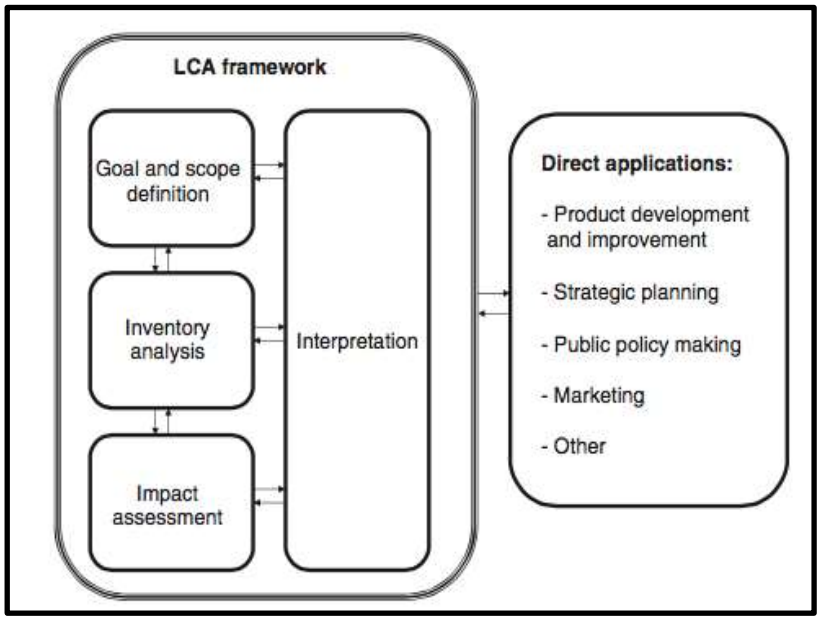

Figure 12: ISO LCA Structure (2006a)

2.6.3. ISO LCA Standard

The development of an international standard for LCA methodology lead to the publication of a number of standards. The relevant ISO standards can be seen in **Table 6.** The initial standards (ISO 14040, ISO 14041, ISO 14042, ISO14043) were produced within seven years after the development of the SETAC code of practice for LCA in

1993 (Bjørn et al., 2018). The first addition of ISO 14040 (1997) was replaced by a slightly updated version in 2006 (ISO, 2006a) and the ISO standards 14041, 14042 and 14043 were superseded by ISO 14044 (ISO, 2006b) which compiled the previous standards into a single document which outlines the requirements and guidelines.

Table 6: ISO LCA Standards

ISO Standard	Title
ISO 14040	Life Cycle Assessment – Principles and Framework
ISO 14041	Life Cycle Inventory Analysis
ISO 14042	Life Cycle Impact Assessment
ISO 14043	Life Cycle Interpretation
ISO 14044	Life Cycle Assessment – Requirements and Guidelines

i) Goal and Scope Definition Phase

The goal and scope definition phase of an LCA is the beginning of an LCA project whereby initial selections are made which establish the working plan of the entire LCA (Guinée, 2002). The 'Definition of goal and scope' is to be present in any given Life Cycle Assessment study as the first phase (ISO, 2006a). In this phase, the fundamental concepts of the study are detailed within the framework of the standard (Klöpffer and Grahl, 2014). Although an LCA is intended to consist of an iterative approach (see double arrows in **Figure 12**), any change of the goal and scope of the study will need to be reported. The product (or service) to be studied is specified, a functional basis for comparative analysis is selected and, typically, the study questions to be answered are developed (Zbicinski, 2006). Some important questions and considerations during the goal definition phase include (ISO, 2006a, SETAC, 1993):

- Purpose of the Study: Why is the study being undertaken? What is the end use of the study? To what audience is the study addressed?
- Publication or other accessibility for the public: Are comparative assertions intended in the study?
- Specification of the product to be investigated: What is the functional unit of the study?
- Scope of the study: What are the system boundaries of the study?

The scope of the study is developed through important information that is relevant to the study, including temporal, geographical and technical coverage, and the level of sophistication of the study in relation to its goal. Lastly, the product (or service) that undergoes the analysis is defined by means of function, functional unit and reference

flows (Guinée, 2002). The definition of the goal and scope of a study provides the initial plan for conducting the Life Cycle Inventory (LCI) phase of the LCA (ISO, 2006b).

ii) Life Cycle Inventory Analysis Phase

As defined by the revised ISO 14040 (2006) standard, a life cycle inventory analysis is the:

> *phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.*

The Inventory analysis is the phase of an LCA whereby the product system (or systems if a number of alternatives are to be considered) is defined. In this phase the system boundaries (initially defined in the goal and scope definition) are used to construct a system flow diagram with unit processes, data is collected for each of the unit processes and calculations are performed (Guinée, 2002). For the unit processes which are multifunctional, an allocation step is provided (Heijungs and Suh, 2002). The end result of an inventory analysis is to produce an inventory table. The inventory table contains a list of all quantified inputs from and outputs to the environment associated with the functional unit in terms of their relevant units (i.e. kgs, mgs, m^3 etc.).

A number of methods are available to conduct an LCI analysis and have been known to generate significantly varying results (Suh and Huppes, 2009). It is therefore important to determine the limitations and advantages of the various methods and select a method that most appropriately suits the specific study application. LCI is a crucial phase in an LCA study since it directly influences the life cycle impact assessment phase as well as the interpretation phase (Gallego-Schmid and Tarpani, 2019).

iii) Life Cycle Impact Assessment Phase

The Life Cycle Impact Assessment (LCIA) is a phase in an LCA study in which the results of the LCI (in particular the inventory table) are refined in terms of environmental impacts (Guinée, 2002). As defined in ISO 14040 (ISO, 2006a), the LCIA is the:

phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

In the first step of LCIA, the impact categories are selected in agreement with the goal and scope definition. The environmental interventions recorded in the inventory table are thereafter classified according to these impact categories (a number of interventions may apply to more than one category). The second step in any impact assessment is classification. Classification involves assigning inventory data to various impact categories that were previously selected. The final mandatory element of an LCIA is characterisation. In the characterisation phase, the indicator is modelled for each category for the various interventions that effect environmental impacts (Hofstetter, 1998). Furthermore, there are optional elements in the LCIA phase including normalisation, grouping and weighting of the indicator results.

According to ISO 14044 standard on LCA, normalisation involves calculating the magnitude of a category indicator results relative to reference information (ISO, 2006a). In the LCA community there is some criticism regarding normalisation due to the choice of normalisation references that could alter the conclusions drawn from the LCIA phase of a LCA study (Pizzol et al., 2016). Normalisation is often used to compare results with a reference situation that is external to or independent from the case studies that could assist in the interpretation and communication of the results. Normalisation can be viewed as a step in LCA that is used to assist in the interpretation of the results, rather than being a part of the "impact assessment", because normalisation does not alter the quantification of the relevant environmental impacts (Pizzol et al., 2016).

iv) Interpretation Phase

The Life Cycle Interpretation of an LCA is the phase where the results of the inventory analysis and impact assessment are used to draw conclusions and provide recommendations with reference to the objective of the study (Klöpffer and Grahl, 2014). The steps of the interpretation phase are outlined in ISO 14044 (ISO, 2006b) as:

1. *identification of the significant issues based on the results of the LCI and LCIA phases of LCA;*
2. *an evaluation that considers completeness, sensitivity and consistency checks;*
3. *conclusions, limitations, and recommendations.*

During the interpretation phase, if it is found that the results of the inventory analysis or impact assessment have not satisfied objectives set out by the goal and scope phase, the inventory analysis will need to be revised with optimised data by means of an iterative approach (Klöpffer and Grahl, 2014). Another option to repeating the inventory analysis would be to adapt the goal and scope in accordance with the information provided (Klöpffer and Grahl, 2014).

v) Strengths and Limitations of LCA

Although LCA is a powerful tool in the advancement towards sustainability, it has a number of limitations as well as strengths (Curran, 2014). The paragraphs that follow deal briefly with the strengths and limitations of LCA.

Strengths

An LCA is a comprehensive environmental management tool that is used to investigate the environmental impacts of services, products and human activity using a "cradle to grave" approach (ISO, 2006a). This is an approach considering all processes from raw material extraction, manufacturing, transportation and distribution, use/reuse, recycling and end disposal (ISO, 2006a). The comprehensive approach of an LCA is what makes LCA a unique tool when compared with numerous other environmental management tools available to decision makers (Curran, 2014).

LCA highlights the potential environmental trade-offs (Curran, 2014). When conducting an LCA, the user is exposed to the extensive and complex nature of the interaction between industrial systems and ecosystems, and the pertinent remedy for

specific situations (Curran, 2014). An LCA is able to identify the potential trade-offs from one phase of the life-cycle to a consecutive phase, for a multitude of environmental issues, over a number of regions that may occur as a result of a decision (Curran, 2014). The ISO structure and framework are ubiquitous in LCA work internationally and provides structure to an investigation. LCA has become an important tool for decision makers in determining when too much or too little emphasis has been placed on a particular environmental aspect (Curran, 2014).

The broad nature of LCA promotes whole system thinking with regard to impact assessment. With the use of data and information, LCA can challenge conventional wisdom in terms of environmentally favourable products and services (Curran, 2014). Furthermore, LCA is able to expand the knowledge base for consumers, organisations and regulators. LCA provides insight to the interconnection of various operations and processes (Ngo, 2012).

Limitations

An environmental LCA considers the potential impacts to the environment due to the extraction of resources, transportation, production, use, disposal and recycling of products. The LCA only deals with one of three pillars of sustainability. These include the environmental, social and economic sustainability pillars. Further analyses such as life cycle costing (LCC) and social life cycle assessment (S-LCA) is required to determine cost implications and social consequences of a product system (UNEP, 2011). However, it may be overly critical to propose that because LCA does not consider economic and social factors that it is a limitation of LCA's capabilities. LCA was, in fact, intentionally developed to consider only the environmental impacts of a system product, service or activity and further including social and economic factors may overload the method (Klöpffer and Grahl, 2014). However, in recent developments elements for a social analysis have been experimentally incorporated.

There are a number of LCA software options and databases that are widely available for LCA practitioners. The most used software options available include SimaPro, Umberto, GaBi and OpenLCA. A problem is, however, the lack of available inventory data for use in LCA (Curran, 2014). Inventory data can be procured from primary and secondary sources. Primary source data refers to data collected from the source, such as

directly from the manufacturer. Secondary data is procured through reports, databases and publications (Curran, 2014). Readily available data that is provided with various software tools makes the LCA analysis an easier process for the user. However, the details of how the data was modelled are not always specified. Assumptions made during data collection and other uncertainties are usually not disclosed in pre-packaged data programs (Curran, 2014).

The transfer of information from trained LCA practitioners to decision-makers may result in misinterpretation of LCA information (Keoleian, 1993). Decision makers often lack the necessary knowledge with regard to environmental effects; furthermore aggregation and simplification techniques may misconstrue results (Keoleian, 1993).

LCA can be a costly and time-consuming exercise. It is unlikely that small businesses would be willing to invest in undertaking LCA studies in order to improve the environmental performance of the service or product that the business provides. The high capital costs of undertaking an LCA study are elevated by the need for databases, software and a professional reviews required to fulfil ISO standards (Keoleian, 1993) .

2.6.4. LCA in South Africa

In South Africa, there is no legislative requirement to undertake LCA studies and there is a limited reference to LCA in government documentation and policies (DEAT, 2004). LCA is, however, regarded as an important environmental tool needed to support scientifically based decisions for implementation in the National Environmental Management Act (NEMA) principles. In South African legislation, it is the responsibility of the waste generator (on a co-responsibility with waste disposal contractors) to appropriately manage and dispose of their waste in a manner that upholds principles of NEMA. It is thus essential that waste generators are entirely aware of the nature and consequences of all waste products (including by-products) produced as a result of their services and/or production operations (DEAT, 2004).

As previously mentioned, LCA is not a legal requirement in South Africa. However, there have been LCA studies undertaken by academic institutions as well as within some sectors of industry. LCA researchers have undertaken LCA studies at the

University of Cape Town, University of KwaZulu-Natal (known previously as the University of Natal), University of Pretoria, Pretoria Technikon and the CSIR (EPS Group) (DEAT, 2004). Large private companies and State Owned Enterprises such as Sasol, Mondi, Impala Platinum and Eskom have undertaken LCA studies (DEAT, 2004).

South Africa is faced with a number of limitations with regard to the use of LCA. It has been found that data is unavailable or not accessible, deemed confidential or lacking in the depth required for the LCA study (Sevitz et al., 2011).

Another important issue with regard to the application of LCA in South Africa is the use of databases that have been compiled in developed countries (predominantly European countries) (Brent, 2004). The application of such databases in South Africa may introduce errors due to a number of reasons, including available technologies and legislation in different countries. However, in South Africa, LCA practitioners often opt for the generic LCA databases available due to the lack of data for local conditions.

2.6.5. Application of LCA in Sanitation Systems

The use of LCA as a tool to determine the potential environmental impacts of sanitation technologies has been widely used for the last two decades. Certain studies have looked at the environmental performance of ecological sanitation systems (Benetto et al., 2009; Remy and Jekel 2008; Gao et al., 2017, Shi et al., 2018) and often compared it to the performance of a conventional activated sludge wastewater treatment system. More importantly, several recent studies have studied and compared the environmental performance of decentralised sanitation systems (Frances, 2012, Lopsik, 2013, Machado et al., 2007, Opher and Friedler, 2016, Roux et al., 2010). The subsequent passages will detail some of the key aspects, important results and limitations of selected decentralised wastewater treatment related LCA studies. It needs to be mentioned that none of the studies shown in Table 9 were undertaken in a South African context. In fact, LCAs undertaken in the South African context have only investigated conventional sanitation (Buckley, 2011).

Table 7: Selected Decentralised Wastewater Treatment LCA studies

Authors	LCA Methodology & Software Used	System/s investigated
Roux et al., 2010	CML Midpoint, Software not mentioned Normalisation method – 1990 global reference values	Conventional, Vertical Flow Constructed Wetlands and Direct Discharge
Frances et al., 2012	CML 2001- Nov 2010 Baseline, GaBi Normalisation used – method not mentioned	Conventional WWTP and BORDA DEWATS
Machodo et al., 2007	CML 2 Baseline 2000, SimaPro Normalisation method – not considered	Conventional activated sludge, slow rate infiltration plant and constructed wetland plant.
Opher & Friedler, 2016	ReCiPe Midpoint and SimaPro Normalisation method – global Normalisation factors	Conventional WWTP, Conventional WWTP with reclamation, Reclamation and source separation alternatives
Lopsik, 2012	ReCiPe and Impact 2002+ (Both used for comparison of results) and SimaPro Normalisation method – Based on impact caused by average European in 2006	Septic tank coupled with hybrid constructed wetland system and Extended Aeration activated sludge treatment system

i) System Boundaries and Functional Units

The system boundary of a study, according to ISO 14044, relates to which unit processes are considered within the scope of the study or product system (ISO, 2006b) and the functional unit is a reference unit which offers a mean for comparison between systems (ISO, 2006b). The importance of subsequent passages is to discuss what unit processes where included and excluded in the system boundaries of selected studies and the functional units that were chosen to provide a means of comparison between the systems.

In a recent review of 43 wastewater related LCA studies (Gallego-Schmid and Tarpani, 2019), all studies included the operation phase of the wastewater treatment technologies considered. This is a significant indication of the often major contribution of the operation phase of conventional activated sludge wastewater treatment plants. Of the

studies considered in this literature review (see Table 9), all included both the construction and operation phases. The broadness of scope and unit processes included varied, Opher and Friedler (2016) considered a large number of unit processes in their study since they considered water supply, wastewater conveyance, wastewater treatment and reclamation. On the other hand, Machado et al. (2007) looked at a much narrower approach and considered only the unit processes in the relevent wastewater treatment systems studied. Other studies considered the construction of the wastewater treatment system, the construction of the sewerage collection system and operation of the wastewater treatment plant (Frances, 2012, Lopsik, 2013, Roux et al., 2010). The only study in this literature review that considered the influence of potable water supply on the overall wastewater treatment system was Opher and Friedler (2016). This important process is often outside of the boundary of typical wastewater treatment related LCA studies, however, the relative environmental impacts shown in Opher and Friedler's (2016) study suggest it should be included and investigated.

It is also relevant to mention specific exclusions of unit processes from system boundaries. In the investigated systems, the only study to include the dismantling and disposal phase was Machado et al. 2007. In their study, dismantling and disposal showed to be the least significant life cycle phase. Gallego-Schmid and Tarpani's (2019) review of wastewater related LCA's showed that important processes such as the construction phase and sludge management are often neglected. All studies included in this literature review considered the construction phase and only one study did not include sludge management (Lopsik, 2013). Importantly, Opher and Friedler (2016) excluded all processes that were similar across all systems studied. The logic behind this exclusion is that it will not influence the comparison of the systems investigated and it will reduce the amount of data uncertainty in their inventory.

With respect to functional units in the selected studies, oftentimes the wastewater treatment systems included for comparison were of differing size and capacity and hence a suitable functional unit would need to take this into account. For this reason, a number of studies (Frances, 2012, Lopsik, 2013, Machado et al., 2007) considered functional units of person equivalent over a particular study period. Similarly, Roux et al. (2010) used the amount of daily nominal organic load since this also provided a

common unit for comparison since both systems treated the same nominal organic load. Gallego-Schmid and Tarpani (2019) recommend that the functional unit should be specific to local conditions in developing countries.

ii) LCI Data and Inputs

The LCI phase of a life cycle assessment involves the "compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO, 2006b). The input flows are the quantities of materials, transportation or energy necessary for each individual process. A clear definition and description of the LCI is crucial to ensure reproducibility of the study and should clearly describe the primary and background data and their sources. As mentioned previously in Section 2.6.3 primary data is gathered directly from the source whereas secondary data is established from databases, reports and literature (Curran, 2014).

For the systems investigated, quantities for the construction and operation phases were often provided in the studies. For the construction phase of sewerage networks, materials such as PVC and PE pipe, cast iron and concrete for sewerage manholes were most common. With regard to constructed wetlands systems, materials such as geomembrane, geotextile, PE and PVC pipes, reinforced concrete manholes (Lopsik, 2013, Machado et al., 2007, Roux et al., 2010) and pump materials were often provided. Expanded lightweight aggregate (LWA) was considered in Lopsik's (2013) comparison of a constructed wetlands system and a conventional wastewater treatment plant. This is important to mention since LWA is not typical of most constructed wetland systems and LWA proved to have a significant influence on the environmental performance of the constructed wetlands system. For conventional treatment systems, septic tanks and other concrete structures, material inputs such as reinforced concrete, plastic, rubble and sand were common (Frances, 2012, Lopsik, 2013, Machado et al., 2007, Roux et al., 2010). With regard to plant operation, commonly included material inputs consisted of electricity for use in mechanical treatment equipment and pumps. Moreover, emissions of BOD, COD, phosphorous, nitrogen and total solids were often provided. Roux et al., (2010) also included a detailed mass balance in their inventory. The significance of providing such a detailed mass balance is when two separate systems with the same inputs result in different outputs (different treatment efficiencies).

Modern software packages and embedded databases were used for most of the selected studies (Frances, 2012, Lopsik, 2013, Machado et al., 2007, Opher and Friedler, 2016, Roux et al., 2010). The abovementioned studies were all process-based LCA's that made use of various versions of the Ecoinvent database to supplement their required data. The Ecoinvent database is very convenient and useful for the studies conducted in a North American and European context. Studies performed in the context of developing countries must rely on generic datasets within Ecoinvent since background data specific to most developing countries are not available.

iii) LCIA Methodology and Normalisation

The LCIA phase of a life cycle assessment involves evaluating the magnitude and significance of the potential environmental impacts for a product system through the life cycle of a product or service. There are a number of LCIA methodologies available for use when conducting an LCA study (Du and Karoumi, 2014). A review of WWT-related LCA studies (Gallego-Schmid and Tarpani, 2019) showed that the CML method was the most commonly used methodology, followed by greenhouse gases characterisation factors. A number of authors have suggested that impact methodologies developed in European countries and the United States such as CML (Guinée, 2002), ReCiPe (Goedkoop et al., 2009), TRACI (Bare, 2011) and Impact 2002+ (Humbert et al., 2012) can have an effect on the results of the study that are site dependent (Lam et al., 2015).

From the studies considered in this literature review, the CML methodology was the most commonly used (Frances, 2012, Machado et al., 2007, Roux et al., 2010). According to Guinee (2002), this method is the most commonly used LCA methodology in LCA. ReCiPe was also used in two of the studies considered (Lopsik, 2013, Opher and Friedler, 2016). ReCiPe is a method that combines the CML and Eco-Indicator 99 methods. For both of the studies that used the ReCiPe method (Lopsik, 2013, Opher and Friedler, 2016) validation of the results was carried out using the Impact 2002+ method. Machado et al. (2007) selected CML 2 Baseline 2000 because of its capability to consider organic matter, nutrients and emissions. Lopsik (2013) selected the ReCiPe methodology and validated the results using Impact 2002+. According to Lopsik (2012), the rationale behind selecting these two methods for

performing the LCA is since ReCiPe includes eutrophication which is an important impact to be considered in wastewater related LCA studies and land use is important in a European context since land availability is scarce. Moreover, prior to the study, Impact 2002+ and ReCiPe had not been used as often in wastewater treatment related LCA studies.

All the studies, except for one (Machado et al. 2007), included a normalisation step. Most studies were relatively clear in the normalisation step factors that were used in order to better understand the relative magnitude of the indicators. Lopsik (2013) made use of normalisation values based on the average European in the year 2000. Since the wastewater treatment technologies were located in Europe this is the most sensible set of normalisation factors to use. Opher and Friedler (2016) and Roux et al. (2010) on the other hand made use of global reference values since local reference normalisation values were not available to be used. It is most accepted to use global reference values when local reference values are not available, however, it is important to mention that these values do not consider local conditions. For the CML 2001 Nov 2010 baseline method used by Frances et al. (2010), normalisation reference values are available for several countries and of course global reference values. Frances et al. (2012) included a normalisation and presented their results, however, no mention was made to the normalisation reference values used to obtain their results..

iv) LCA Study Results

Machado et al. (2007) compared a conventional wastewater treatment plant with a constructed wetlands and slow rate infiltration system. The activated sludge system showed that a major portion of the environmental impacts were attributed to the operation of the plant (requirement of energy for aeration equipment) and less than 20% of impacts were attributed to the construction phase. On the other hand, for the constructed wetlands system and slow rate infiltration systems, operation and maintenance had a more marked impact across most impact categories. Dismantling and disposal showed to be less significant across all three systems (less than 20% for most impact categories).

An LCA study by Roux et al. (2010) involving the comparison of VFCW to conventional activated sludge system produced some interesting results. The results

demonstrated the major importance of eutrophication in VFCW from the incomplete removal of nutrients. However, overall the VFCW produces a better environmental profile across all other CML midpoint impact categories. Secondly, the VFCW main life cycle stages were compared against each other as well as the sewer network impacts. Interestingly, the impact of the sewer network was a major influence in all impact categories except for eutrophication and to a lesser extent in global warming. These results were considerably different to a similar study performed by Lopsik (2013). In this study (Lopsik, 2013), the activated sludge performed markedly better across most impact categories. However, it must be noted that in Lopsik's (2013) study, the use of a light weight expanded aggregate material (LWA) was used as the filter material as opposed to gravel and sand which is typical of most constructed wetlands. Importantly, the large amount of energy and crude oil required in the production of LWA resulted in the largest impact across most impact categories. Replacement of this material with sand and gravel would result in an average of 15.86% reduction across impact categories. Moreover, in the analysis of results it showed that the construction of the constructed wetlands is more significant than the operation of the plant which opposes the results found by Roux et al. (2010).

Opher and Friedler (2016) compared four separate scenarios considering a base scenario of conventional wastewater treatment and discharge with various wastewater treatment and consequent reuse and reclamation methods. The study showed that the overall systems impact (looking at water treatment, potable water supply, wastewater treatment and reuse) can be reduced by an average of 18% by using non-potable urban water reuse of WWTP effluent and can be further improved by applying urban greywater reclamation. The three most significant impacts across the study included marine ecotoxicity, freshwater eutrophication and marine eutrophication. Freshwater eutrophication impacts were mainly attributed to phosphate emissions from electricity production, more specifically, landfilling of spoil from coal mining and wastewater leakage to groundwater. Aquatic ecotoxicity is attributed to heavy metals emitted to water bodies by process in the supply chain of electricity production (namely in coal mining disposal in landfills). The importance of this study is that it is the only study to consider in detail the influence of potable water supply on the overall system.

A study has previously investigated the environmental performance of a BORDA DEWATS and compared it to a conventional wastewater treatment plant (Frances, 2012). The results showed that global warming is the most significant impact category followed by aquatic ecotoxicity and human toxicity potentials. For the BORDA DEWATS, construction and operation stages contribute largely for various impact categories. However, it is fair to say that operation contributes more to the overall environmental profile since operation is more significant in the impact categories of eutrophication, global warming, aquatic ecotoxicity and terrestrial ecotoxicity while construction significantly contributes to acidification, ozone depletion, photochemical ozone formation and human ecotoxicity potentials. The BORDA system was shown to reduce global warming more than the conventional wastewater treatment system. However, since the BORDA DEWATS does not entirely remove nutrients before discharge to the environment, eutrophication was shown to be higher in the DEWATS (Frances, 2012).

In summary, from LCA results considered in the literature review of this study reported that the operation phase was more significant than the operation phase (Frances, 2012, Opher and Friedler, 2016, Roux et al., 2010), whilst other studies demonstrated that construction contributed more to environmental degradation (Lopsik, 2013, Machado et al., 2007). In the studies that included a normalisation phase, results showed the importance of freshwater and marine aquatic ecotoxicity (Frances, 2012, Lopsik, 2013, Opher and Friedler, 2016), eutrophication (Lopsik, 2013, Opher and Friedler, 2016, Roux et al., 2010) and less frequently global warming showed to be significant (Frances, 2012).

v) Improving LCA Quality

A comprehensive review of WWT-related LCA studies in developing countries has provided some insight into improving the quality of LCA studies (Gallego-Schmid and Tarpani, 2019). The study demonstrated that in most LCA studies the goal and system boundaries were defined to the required detail, however, important stages for certain technologies such as construction and sludge management were frequently excluded from the analysis. Moreover, the functional unit should be site specific and defined

according to local conditions (Gallego-Schmid and Tarpani, 2019). With regard to LCI analysis, a more succinct description of data sources and technical parameters could significantly improve the quality of LCAs along with the accountability of GHG (Greenhouse Gas) emissions (Gallego-Schmid and Tarpani, 2019). The estimation of site-specific databases, characterisation factors and weighting values coupled with the use of background databases embedded in LCA software has the potential to greatly increase the accuracy of WWT-related LCAs in developing countries (Gallego-Schmid and Tarpani, 2019). Finally, the use of an uncertainty analysis is endorsed since the analysis assists LCA practitioners in being able to understand the influence of their available datasets (Gallego-Schmid and Tarpani, 2019).

2.7. Water Consumption and LCA

2.7.1. Greywater and Rainwater Harvesting

South Africa is a water scarce country and in current years cities have experienced major water restrictions as seen in Cape Town in 2018 (Rodina, 2019). Not only is water a scarce resource, the production of water supply to potable municipal water standards requires large amounts of electricity for the treatment and transport (pumping) to end users (USEPA, 2013). For these reasons, several studies around the world have investigated methods of reducing the dependency on municipal water supply and their economic and environmental viability (Anand and Apul, 2011, Crettaz et al., 1999, Gao et al., 2017).

Some LCA studies have considered the use of rainwater harvesting as a means of reducing potable water demand (Anand and Apul, 2011, Crettaz et al., 1999, Gao et al., 2017), whilst others have considered greywater treatment and reuse (Kobayashi et al., 2020, Opher and Friedler, 2016). In all the studies that considered rainwater harvesting, the results showed that rainwater harvesting underperforms from an environmental perspective and is also often not economically justified (Anand and Apul, 2011, Crettaz et al., 1999, Gao et al., 2017). The relatively poor environmental performance (when compared with a business as usual potable water supply scenario) is shown to be related to the increased energy demands required in pumping from local household pumps. The pressure required to supply water to toilet cisterns is typically in the order of 1 bar, whilst the pressure required for garden irrigation systems is closer to 4 bar (Crettaz et

al., 1999). For this reason, it is recommended that the utilization of harvested rainwater for garden irrigation should be avoided. Interestingly, the studies (Anand and Apul, 2011, Crettaz et al., 1999, Gao et al., 2017) all suggested the best means (from an environmental perspective) to slightly reduce dependence on municipal water is to provide low flushing interventions. The issue, however, is that flushing water often only accounts for a relatively small portion of potable water demand. Kobayashi et al. (2020) considered toilet flushwater to account for only 27% of demand, BORDA engineers responsible for the design of the NLM DEWATS plant estimated at 25% whilst the local Municipality (eThekwini Municipality, 2009) recommends a 25% estimation of flushwater.

Other LCA studies focused on the environmental performance of greywater reuse at different scales (household, neighbourhood and community levels) (Kobayashi et al., 2020). It was shown that the electricity mix of a local region and the amount of greywater reused were significant parameters in the environmental profile when comparing a constructed wetlands, membrane bioreactor (MBR) unit and conventional wastewater treatment plant. Since the MBR treated greywater to a better standard, the treated greywater could be used across more applications than the constructed wetlands effluent. The effluent from the constructed wetlands system was deemed suitable for irrigation only whilst the effluent from the MBR was deemed suitable for irrigation and further applications. When considering the scales of usage, community reuse resulted in a better environmental profile than household level reuse. The reason for the poorer environmental performance at a household level is due to the larger construction requirements of many decentralised systems and lack of economies of scale. The study showed that increasing the amount of greywater reuse (and hence reducing potable water dependence) across different applications improved the environmental profile of the system. Therefore, using an MBR unit at community level and reusing the treated greywater for as many applications possible resulted in the best environmental performance when comparing systems. However, when comparing the MBR and the constructed wetlands wherein both systems treated greywater is used for irrigation only, the constructed wetlands slightly outperforms the MBR from an environmental perspective.

2.7.2. Potable Water Production

Although in most wastewater related environmental LCA studies domestic water supply is often excluded from the system boundaries, some studies have shown potable water to have a considerable influence on the overall environmental performance of wastewater treatment systems (Opher and Friedler, 2016, Roux et al., 2010). Friedrich (2001) performed an LCA study that investigated the environmental performance of two methods of potable water production in a South African context and more specifically in the eThekwini Municipality. The results of this study showed that electricity generation dominated the environmental burdens across all impact categories considered. A number of recommendations were provided regarding the improvement of the potable water production system including increasing the overall efficiency of mechanical components at the water treatment plants and selecting design options that aim to reduce the electricity consumption of the plant (Friedrich, 2001).

2.8. Summary

South Africa is facing major wastewater and sanitation issues. Current backlogs, exponential population growth and the poor state of current wastewater treatment facilities represent a few of the problems faced in South Africa. Moreover, in urban slum dwellings and sporadic rural villages, conventional sanitation fails to meet the sanitation needs of South African citizens. Drastic interventions are required to ensure South Africa achieves the United Nations Sustainable Development Goals and goals set by the South African government in the National Development Plan.

A number of sanitation solutions and technologies have been proposed by various organisations and groups in order to address sanitation issues experienced in developing countries. Decentralised Wastewater Treatment Systems have been implemented successfully in many developing countries in Asia and Africa. DEWATS is not the most favourable solution everywhere, however, when operation and maintenance is an issue, DEWATS is unquestionably a favoured solution.

LCA can be used to establish environmental information regarding DEWATS. It is important to investigate the environmental impacts DEWATS has on the environment

to assist relevant decision makers and to provide recommendations for areas of improvement regarding its environmental performance. By performing an LCA study on a DEWATS in a South African context, this study aims to provide relevant decision makers and technical personnel with the aforementioned information. It needs to be mentioned that currently there is no other LCA study investigating DEWATS in the country and therefore this research aims to address this knowledge gap.

CHAPTER 3: CASE STUDY OF NEWLANDS MASHU

This chapter details the decentralised wastewater treatment system analysed in this study. An overview of the specific components is provided as well as specific information regarding the Newlands Mashu site.

3.1. Background to Newlands Mashu DEWATS

The Pollution Research Group (PRG) in the School of Chemical Engineering at the University of KwaZulu-Natal has acquired two decades of valuable experience in the field of pilot-scale ABR systems (Pillay et al., 2014). Due to the PRG's theoretical experience in ABR technology, in 2007 the group was tasked to manage research activities for BORDA DEWATS plants. Since there was scarce information regarding the performance of the local DEWATS system, a pilot BORDA DEWATS project was proposed. BORDA were responsible for providing designs for the plant, eThekwini Municipality provided an appropriate piece of land and PRG were tasked with the theoretical analysis of the pilot plant. The Newlands Mashu DEWATS was monitored over four separated research phases under the Project K5/2002 by the Pollution Research Group. The studies were commissioned by the Water Research Commission (WRC).

In 2009, a favourable piece of land was sited and construction began on the Newlands Mashu technical evaluation DEWATS plant in collaboration between BORDA, eThekwini Water and Sanitation and PRG. By 2010, construction of the Newlands Mashu DEWATS plant was completed. The aim for the project was to develop a further understanding of the performance of the DEWATS system through detailed monitoring and establishing the operational and maintenance requirements. Furthermore, the use of treated wastewater for urban horticulture is also evaluated at the plant (Pillay et al., 2014).

The Newlands Mashu Research Site provides a suitable environment that allows for the study, development and evaluation of sanitation systems, resource recovering and agricultural recycling. The information gathered from the Newlands Mashu site also ties into the eThekwini Municipality's long term strategy to develop appropriate sanitation systems for existing and future housing projects (PRG, 2015).

3.2. Newlands Mashu DEWATS

Newlands Mashu (NLM) is a site in eThekwini Municipality that was selected for construction of a DEWATS system that receives wastewater from 84 low to medium income households in Newlands, KwaZulu-Natal. The project at Newlands Mashu is a collaboration between BORDA, eThekwini Water and Sanitation and the Pollution Research Group. **Figure 13** shows a photograph of the general overview of the site.

Figure 13: General overview of the NLM DEWATS site (Photo courtesy of BORDA).

3.2.1. Location

The Newlands Mashu DEWATS plant is located on 71 John Dory Drive in Newlands, KwaZulu-Natal (**see Figure 14**). The site was chosen by the eThekwini Municipality due to land availability and the relatively easy access to domestic wastewater from neighbouring properties via a sewer pipe. Moreover, the position of the main sewer is ideally located such that effluent from the plant can be discharged back into the waterborne sewerage system if required for maintenance purposes or in an emergency (Pillay et al., 2014).

Figure 14: Location of the wastewater catchment (Source: Pillay et al., 2014)

3.2.2. Wastewater Catchment Area and Load Estimation

The location of the wastewater catchment area can be seen in **Figure 14**, demarcated by the yellow line, and the boundary of the DEWATS plant can be seen in red to the east. The planning calculation for the hydraulic loading of the units are summarised in **Table 8**. The calculation uses an estimation of five persons per household and a per capita consumption of 90 litres per day. Allowing for an additional 10% reserve, the overall wastewater influent estimation is shown as 41.6 m^3/d. The measured daily average flow rate was recorded at 35.9 m^3/d (Reynaud and Buckley, 2015) and is relatively close to the estimation without the reserve allowance (37.8 m^3/d).

Table 8: Planning calculation used for Newlands Mashu Plant (source: Pillay et al., 2014)

	Units	Persons per household	Total Persons	l/cap/d	m^3/d
Houses	84	5	420	90	37.8
Total	84		420		37.8
Reserve	10%		42		3.8
Calculation base			462	90	41.6

3.2.3. Process Overview

The Newlands Mashu (NLM) DEWATS process diagram is shown in **Figure 15.** Domestic wastewater from 84 households is diverted from a sewer network comprising of approximately 1641 meters of sewerage pipeline (see **Appendix F**) and accompanying manholes. As shown in the process diagram, the DEWATS system was designed such that influent wastewater can be diverted back into the trunk sewer main when required. The mechanism which allows for this to happen is a side plate within a chamber prior to the ABR unit. Certain DEWATS designs have sometimes included screening and degritting components prior to biological treatment in the ABR (Singh et al., 2009), however, the NLM design does not include this and relies on the settling unit to temporarily contain solid waste materials and grit material.

The wastewater initially enters the settling unit when it reaches the plant. In the settler, mechanical treatment occurs through sedimentation of easily settleable solids and biological treatment occurs through contact of fresh wastewater and active sludge biomass (BORDA, 2017). Sludge draw-off pipes are embedded at the bottom of the settling compartments for periodic desludging. The sludge that is drawn-off from the settler is discharged into the adjacent sludge drying bed. The sludge percolate is discharged into the main sewer line.

Three separate ABR trains are provided at NLM to ensure flexibility during maintenance events. The arrangement of three separate ABR trains was also useful for research purposes. ABR trains 1 and 2 comprise of seven compartments, whilst ABR train 3 has four compartments. The performance of the ABR trains were separately analyzed during the course of studies undertaken by Pillay et al. (2014) over a number of Research Phases. Research Phase 1, 2 and 4 carried out by Pillay et al. (2014) made use of all three ABR streams. However, in Research Phase 3, all influent wastewater diverted into ABR train 1 to determine the performance of the system under shock hydraulic loading. Subsequent to the ABR train, two anaerobic filter compartments are provided for further biological treatment and polishing

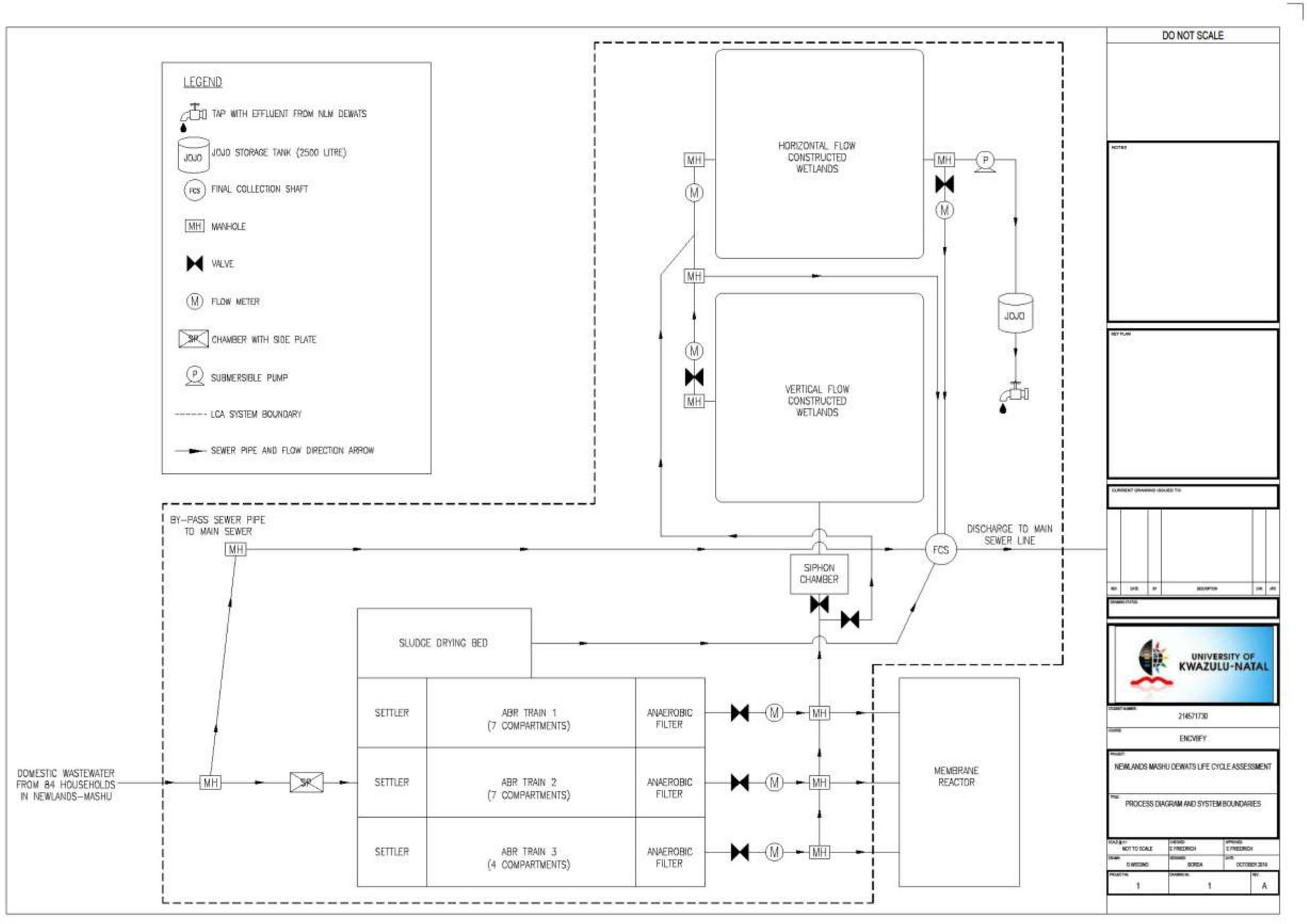

Figure 15: Operating Diagram of Newlands Mashu DEWATS

Following after the anaerobic filter, the wastewater treated in the ABR unit passes through flow meters. A flow meter is provided for all three of the trains as shown in the process diagram. A single flow meter at the inlet of a treatment works is common practice, however, several flow meters throughout a wastewater treatment plant is rather uncommon. However, since this is a pilot plant, it is important to measure the flow rate throughout the plant.

A dotted line in **Figure 15** marks the system boundary for the components that are included in this environmental life cycle assessment study. Subsequent to the flow meters, a series of distribution manholes allow wastewater to be diverted into a membrane reactor or into the constructed wetlands. As the demarcated boundary shows, the membrane reactor is excluded from the scope of this study and is omitted from the environmental life cycle assessment. Therefore, in this study, it is assumed that wastewater is always diverted into a series of constructed wetlands.

Effluent from the distribution manholes is then directed towards the constructed wetlands. As shown in **Figure 15**, wastewater can be directed immediately to the VFCW, it can be directed immediately into the HFCW or the wastewater can be diverted through both constructed wetlands consecutively. The aforementioned combinations can be achieved due to the configuration of valves provided by the BORDA design engineers. In the constructed wetlands, aerobic and facultative decomposition occurs.

Finally, at the distribution outlet of the HFCW, the effluent from the DEWATS plant can be discharged in two ways. The effluent can be discharged into a sewer pipe that leads to the final collection shaft. The final collection shaft is connected to a bulk sewer pipeline that leads to a conventional wastewater treatment plant. Or the effluent can be lifted by a submersible pump to a storage tank (Jojo tank) where the treated water is distributed to various standpipes for reuse throughout the site.

3.2.4. Plant Components

i) Settling Unit

The Newlands Mashu plant makes use of a settling tank for primary treatment. The settling tank consists of two rectangular chambers. The first chamber is 1.5m wide and its length is 7.82m. The second chamber is 1.34m wide and it shares the same length as the first chamber. Tayler (2018), suggests that settling units should provide between 8 to 16 hours hydraulic retention time (depending on flow) and an additional 50 per cent allowance for sludge storage. The NLM DEWATS provides approximately 20 hours retention time. Assuming an average daily inflow of 35.9m³/d, the calculated settler storage volume amounts to 29.8m³.

ii) Anaerobic Baffled Reactor

Biological treatment is carried out in the ABR and subsequent anaerobic filter due to its ability to remove wastewater contaminants (Barber and Stuckey, 1999). As previously mentioned, ABR trains 1 and 2 are divided into seven compartments and ABR train 3 is divided into four compartments. Chamber widths in ABR trains 1 and 2 were designed as 0.7m and overall chamber width of 7.5m was chosen. The effective volume of the baffled reactor was designed as 56.7 m^3 providing a retention time of 31 hours. The invert level of the inlet pipe into the settler is 1.95m above the bottom of the tank and the invert level of the outlet pipe from the anaerobic filter is 1.80m above the tank.

The ABR unit, housed in the same unit as the settler and the anaerobic filter, is constructed of reinforced concrete. The compartments of the ABR are separated by reinforced concrete walls. Flow between compartments is facilitated by PVC-U pipes that are embedded in the walls. **Figure 16** shows the configuration of the ABR compartments and the difference between the seven compartment trains (trains 1 and 2) and the four compartment train (train 3).

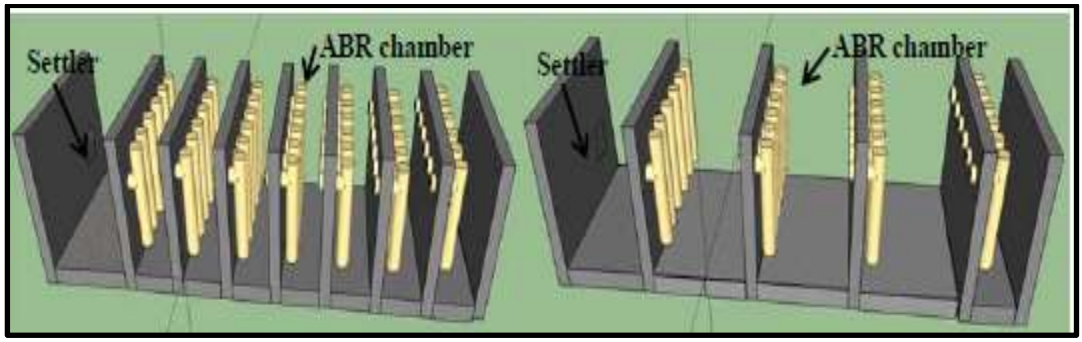

Figure 16: Representation of ABR Trains 1 and 2 (left) and ABR Train 3 (right) at Newlands Mashu DEWATS

Cast iron manhole covers are used throughout the ABR unit. In total there are 18 identical access manhole covers on the ABR section measure 0.51m X 0.71m X0.025m (L X B X H).

iii) Anaerobic Filter

An anaerobic filter (AF) is a common feature of typical BORDA DEWATS plants and usually follows after the anaerobic baffled reactor. The AF is suited to domestic wastewater that has a low content of suspended solids. In terms of the processes at work, the AF combines solids removal with digestion of dissolved organic material (BORDA, 2017). At NLM, two AF compartments are provided for biological polishing after each ABR train. The depth and length of the filter tanks are both 1.80m and the combined total width of the tank is 7.50m providing a net volume of 26.66 m^3. The filter height was calculated to be 1.25m high.

Similar to the settler and ABR, the AF was housed in a reinforced concrete structure. The wastewater is conveyed from compartment to compartment through PVC-U pipes embedded in the separating walls. The filter material used is a perforated concrete slab as shown in **Figure 17**. The perforated concrete slab rests on brick plinths.

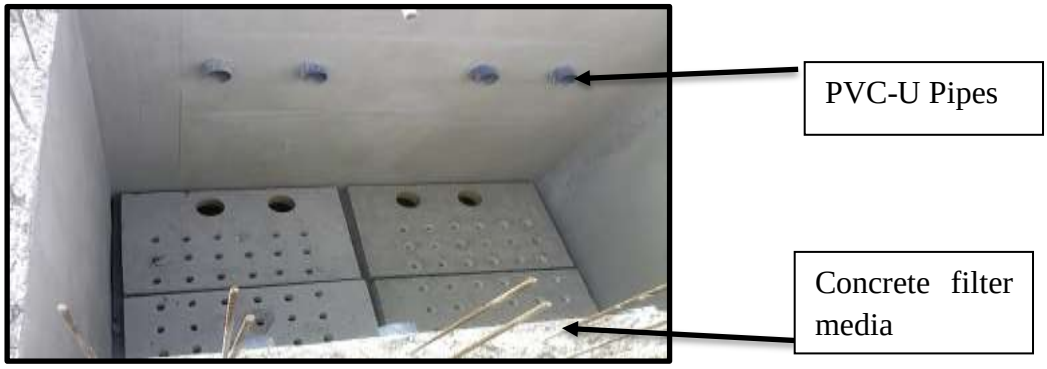

Figure 17: Photograph of a compartment of the anaerobic filter during construction showing the PVC-U pipes, perforated concrete filter media and reinforced concrete housing unit (photo courtesy of BORDA)

iv) Constructed Wetlands

Tertiary treatment involves treating wastewater with a low suspended solids content that requires subsequent nutrient removal in an attempt to meet relevant discharge standards. Further to nutrient removal, tertiary treatment is also used for pathogen removal. Planted Gravel Filters (PGF) are the typical option used for this treatment step. The Newlands Mashu DEWATS plant was designed to have two different types of constructed wetlands (Vertical and Horizontal Flow Constructed Wetlands) that can be operated independently from each other. It is important to note that the constructed wetlands were designed to manage one third of the total design flow, or otherwise the entire flow through a single flow train.

Vertical Flow Constructed Wetlands

The Newlands Mashu DEWATS plant also has a Vertical Flow Constructed Wetland (VFCW) on site. A VFCW consists of a planted filter bed that is drained at the bottom of the bed. Wastewater from the AF flows through to the siphon chamber preceding the VFCW. The wastewater is then dosed intermittently through four parallel HDPE pipes on top of the VFCW. The intermittent dosing of the VFCW is achieved through a dosing device installed inside the siphon chamber. In order to equally distribute the water throughout the VFCW, 14mm holes are drilled into the HDPE pipes.

The siphon chamber is constructed of brick walls and a reinforced concrete base as shown in **Figure 18**. The perimeter of the VFCW is bound be a 150mm brick wall laid on a concrete strip foundation. The top layer of the VFCW is 8 m^3 of washed

gravel (grain size 19-25mm) and the filter layer is sieved river sand accounting for a volume of 40 m^3. An HDPE geotextile membrane is laid at the bottom of the wetland. The geotextile material (300g/m^2) covers an area approximately 100m^2. Canas indica, an aquatic plant suitable for the VFCW, was planted in the constructed wetlands. The siphon chamber feeds wastewater through approximately 61m of HDPE pipe.

Figure 18: Left - Siphon chamber and VFCW during construction at NLM DEWATS. Right – Plant material at NLM in June 2019.

Horizontal Flow Constructed Wetlands

Wastewater from the Anaerobic Filter can be direct to either the Horizontal Flow Constructed Wetlands (HFCW), Vertical Flow Constructed Wetlands (VFCW) or both simultaneously for final treatment. HFCW relies on biological conversion, physical filtration and chemical adsorption to remove nutrients and treat the wastewater.

The HFCW is fed by a 110mm PVC-U pipe that is laid horizontally across the width of the HFCW. The aforementioned PVC-U pipe is perforated with 3mm openings to allow even distributed throughout the wetlands. The sides of the HFCW are sloped at 35 degrees and shaped as shown in **Figure 19**. The perimeter of the HFCW is bound by a 150mm brick wall laid on a concrete strip foundation. An HDPE geotextile membrane is laid at the bottom of the wetland. The geotextile material (300g/ m^2) similarly covers approximately 100 m^2. Crushed stones were used as filter material.

Similar to the VFCW, Canas indica, was planted in the HFCW. The outflow from the wetlands can either be pumped from the outlet sump to a Jojo tank and used for irrigation or the final effluent can be directed into the trunk sewer main that runs through the site.

Figure 19: Left - Excavation during construction of the VFCW and HFCW showing the angled side slope at NLM DEWATS Right – Photograph showing the brick and crushed stone material used in the HFCW (Photo courtesy of BORDA engineers).

v) Sludge Drying Bed

The sludge drying bed (SDB) is used to dewater and stabilise sludge from the settling unit. Wet sludge is discharged from the settling tank into the sludge drying bed (adjacent to the ABR unit) and is left on the drying bed in order to reduce the liquid content of the sludge. The reduction in liquid content occurs in two ways. Firstly, percolation occurs and the liquid fraction seeps through the sand bed filter and secondly evaporation occurs on the surface of the sludge. Percolation is dominant in the preliminary stages of dewatering and, thereafter, evaporation is of greater importance once most of the free water has been removed. Percolation from the sludge is directed to the final collection shaft.

The SDB is 6m X 2m X 1.38m (L X B X H) providing a surface area of $12m^2$. The bottom of the SDB is sloped at 1:20 toward a central 110mm PVC-U pipe. The

structure (See **Figure 20**) of the SDB is constructed of reinforced concrete material. A 20mm layer of river sand and 200mm layer of gravel is provided in the sludge drying bed. Steel guard rails are also provided around the perimeter of the SDB.

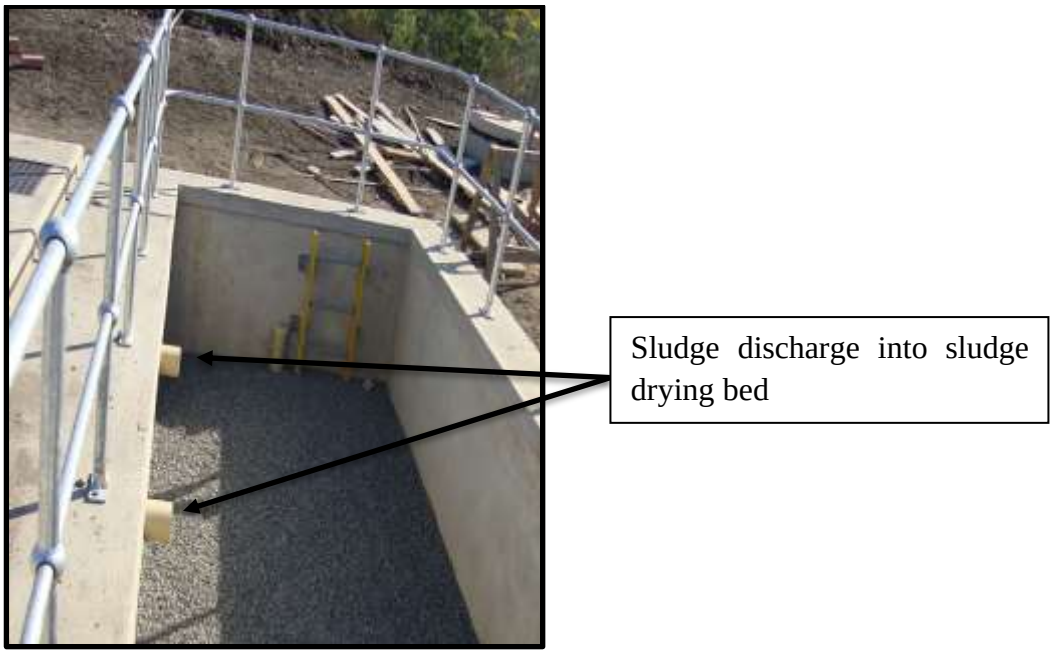

Figure 20: Sludge drying bed at NLM DEWATS showing the discharge pipes, gravel material and steel guard rails (Photo courtesy of BORDA engineers)

vi) Effluent Reuse

A submersible pump inside the effluent chamber of the HFCW delivers treated effluent to a water storage tank near the entrance of the site. The submersible pump (see **Figure 21**) operates between flow rates of 8-10m^3/h and a maximum hydraulic head of 10m. An integrated floater with a level switch is also provided to automate the pump when the wastewater in the chamber reaches a specific level. The pipe that delivers the effluent to the storage tank is a 50mm HDPE pipe and is approximately 60m in length. The storage tank is made of low linear density polyethylene (LLDPE) and stands on a reinforced concrete base as shown in **Figure 22.**

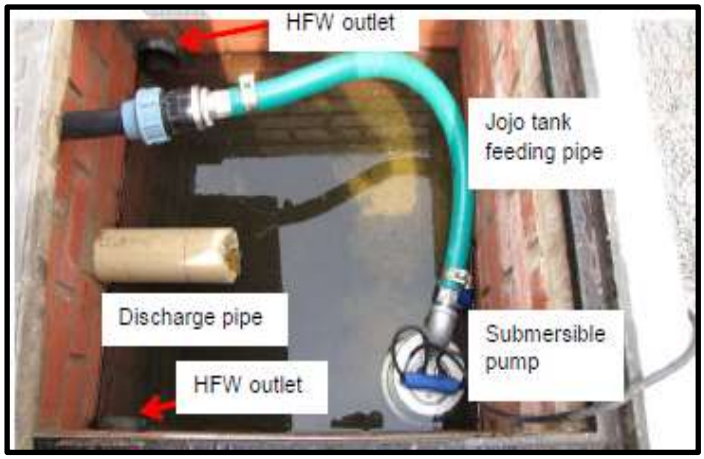

Figure 21: Submersible pump inside HFCW outlet chamber (Photo courtesy of BORDA engineers)

From the storage tank, the treated effluent is then delivered by gravity to various standpipes throughout the Newlands site. The pipe that conveys treated effluent to standpipes throughout the site is 25mm HDPE pipe. An example of a standpipe near the wash area adjacent to the ABR is also shown in **Figure 22** below.

Figure 22: Right - LLDPE storage tank ("Jojo Tank") with reinforced concrete base near entrance of NLM DEWATS. Left – Standpipe at NLM that receives treated effluent from the storage tank via gravity flow.

vii) Flow Control and Measurement Components

Side Plate

Since the Newlands Mashu site is a pilot plant, there are a number of components that were included for the monitoring of the plant. Most of these components would not form part of a typical BORDA DEWATS design. The first component to mention is the distribution manhole which is located at the head of works of the plant. The distribution manhole has a side plate (see **Figure 23**) which can be operated by hand in the event that wastewater influent needs to be diverted to the trunk sewer main.

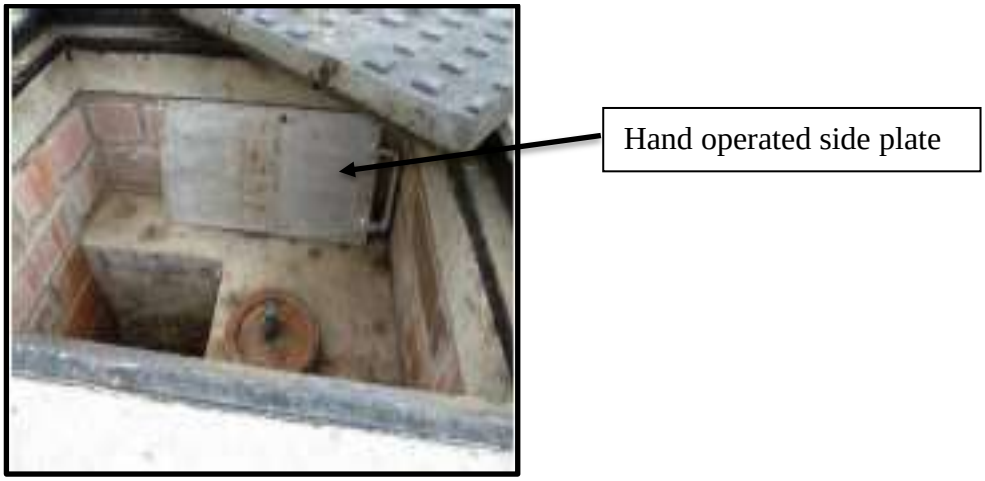

Figure 23: Distribution manhole and side plate at the head of works at Newlands Mashu DEWATS.

Flow Meters

There are a number of flow meters located throughout the Newlands Mashu DEWATS plant. A typical wastewater treatment plant may usually have two flow meters, one flow meter at the head of works and one flow meter at the discharging point of the works. Since the Newlands Mashu site is a research-based facility that investigated a number a different flow paths during different research phases, it is important that relevant flow monitoring devices were placed at appropriate locations at the plant. An example of the type of flow meter seen at Newlands Mashu (photo refers to the meter after ABR Train 3) can be seen in **Figure 24**. A total of six flow meters exist at Newlands Mashu DEWATS plant as shown in the process flow diagram earlier in **Figure 15.**

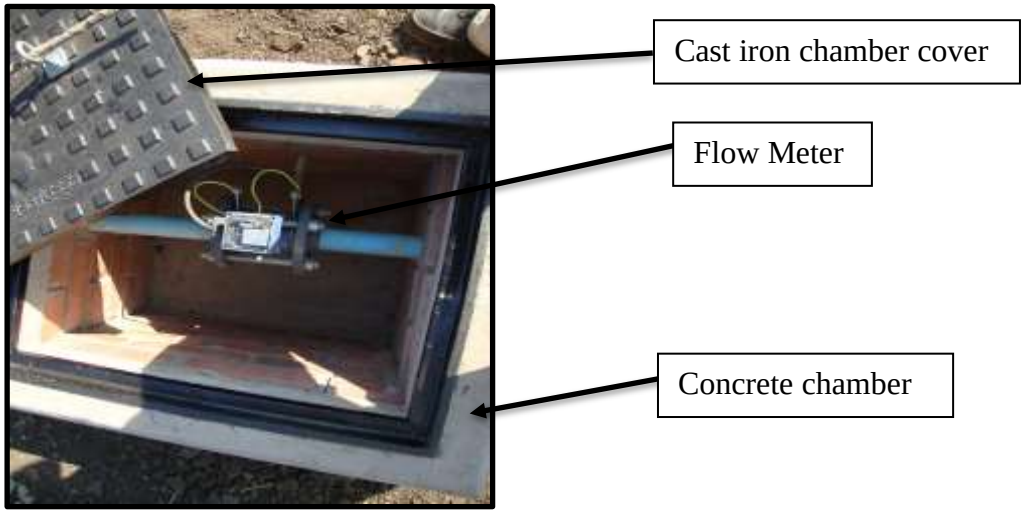

Figure 24: Flow meter as seen at Newlands Mashu DEWATS after ABR Train 3.

Valves

In order to divert wastewater to the required components, BORDA engineers included an arrangement of valves in their design. The arrangement of valves on the sewer pipes ensured that various components throughout the plant can be by-passed if necessary. For example, the current NLM DEWATS design allows both HFCW and VFCW to be used consecutively or in isolation. This is achieved by the arrangement of flow control valves shown in **Figure 25** below. The valves shown in **Figure 25** are upstream of the siphon chamber and allow wastewater to either be directed into the chamber or to be by-passed to the HFCW.

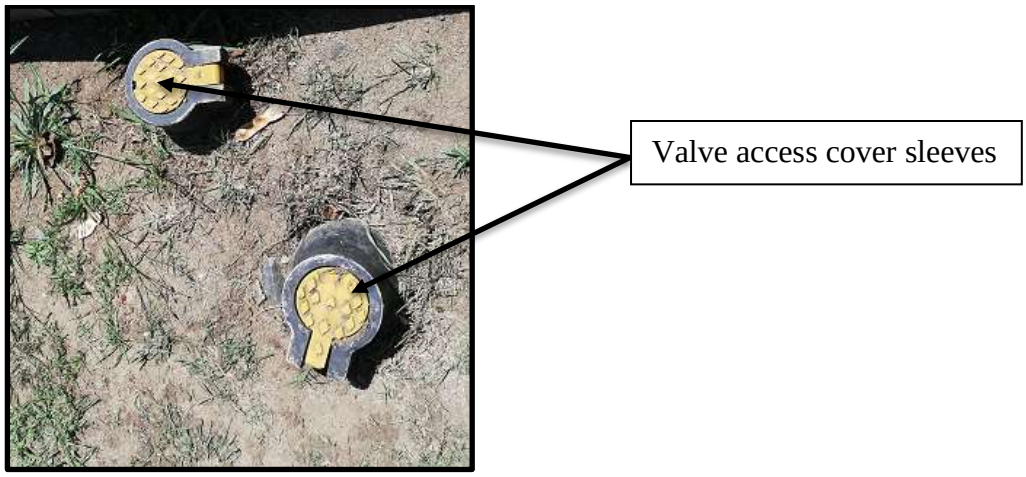

Figure 25: Flow control valves immediately before the siphon chamber at NLM DEWATS.

3.3. Plant Seeding

The settling tank was seeded with anaerobic sludge from the KwaMashu WWTP. Additionally, in ABR trains 1 and 2, the first two compartments were seeded and the first compartment of ABR train 3 was seeded. The seeding process started on the 23rd of September 2010 and was completed by the 27th of September 2010 (Pillay et al., 2014). The eThekwini Water and Sanitation (EWS) unit provided a honeysucker truck to facilitate in the transport of anaerobic sludge. Figure 26 shows the honeysucker truck at NLM DEWATS. Five honeysucker (capacity of $5m^3$) truck loads were transported to the plant. The hose was used to withdraw anaerobic sludge from the secondary anaerobic digester at KwaMashu WWTP. The KwaMashu WWTP is located 14km from the NLM DEWATS site. The aforementioned settling tank and ABR compartments were filled to approximately one meter.

Figure 26: Honeysucker truck provided by EWS to collect anaerobic sludge in order to seed the NLM DEWATS (Photo courtesy of BORDA engineers)

3.4. Operation and Maintenance (O&M)

The operation of the plant refers to all services which are required to run the plant. Maintenance of the plant refers to all activities necessary to preserve the original condition as well as assessing the current state of the facility. BORDA DEWATS plants are designed to minimize operation and maintenance requirements, however, operation and maintenance is still necessary at most plants to ensure the plant fulfills its desired function. Typical maintenance activities observed at NLM DEWATS

include inspection and cleaning, repair or exchange of faulty appliances, desludging and descumming, controlling and monitoring procedures (Sananikone, 2012). O&M activities that may potentially impact the environmental performance of the NLM DEWATS are included and discussed in the sections that follow. A full description of the O&M requirements of the NLM DEWATS is not provided as it was beyond the scope of this study.

3.4.1. Settler

Apart from primary biological treatment and settlement, the settler is also used to collect large debris and trap foreign materials. The materials that accumulate in the settler require removal at regular intervals. According to the operation manual compiled by BORDA engineers (Sananikone, 2012), manholes in the settler require weekly inspection and subsequent removal of foreign material such as plastic and debris (shown in **Figure 27)**. The collected solid waste material is stored temporarily in a disposal bin and collected weekly by DSW (Cleansing and Solid Waste Unit of eThekwini Municipality).

Figure 27: Foreign material accumulated inside the initial settling compartment at NLM DEWATS.

Further to the removal of foreign material, descumming of the accumulation of fats, oils and grease in the compartments of the settler is also required at weekly intervals. Complete desludging is undertaken yearly. When desludging is required, the

desludging pipe is removed from its socket and sludge is discharged into the adjacent sludge drying bed.

3.4.2. ABR and AF

According to the Sananikone (2012), the ABR and AF at NLM requires inspection at monthly intervals. Inspection requires opening of each manhole within both the ABR and AF and stirring to encourage heavier particles to settle. Similar to the settler, any foreign materials are to be removed and disposed into a temporary storage unit before being collected by DSW for subsequent disposal at a landfill site.

The sludge height in the final ABR chamber is also checked during this inspection. The manhole is opened and a stainless steel rod is placed vertically inside the chamber with the bottom of the rod touching the invert level of the chamber. If the sludge height is too high in the final chamber, the performance of the plant may be reduced and desludging may be required. Wastewater inside an AF compartment is withdrawn and clean domestic water is discharged into the compartment. Once the clean water has filled the compartment, the suction hose of the pump is placed inside the down-flow pipe. As shown in the illustration in **Figure 28**, clean water is continuously recycled in order to clean the filter material. This flushing process is typically done for 10 minutes per compartment.

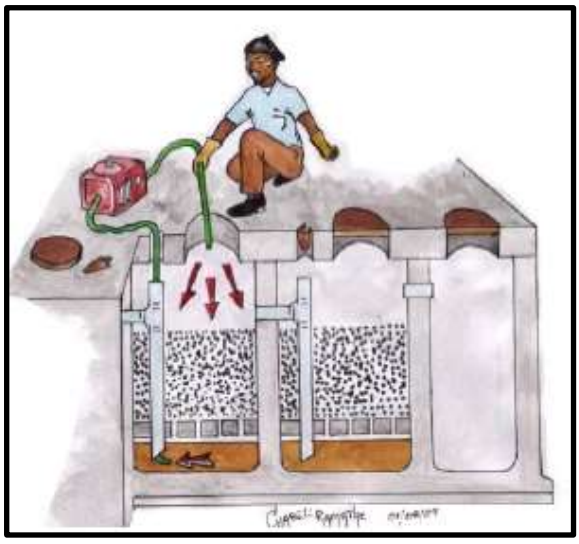

Figure 28: Illustration of the procedure for flushing out the anaerobic filter (Sananikone, 2012)

3.4.3. Sludge Drying Bed

Although no specific mention is made with regard to O&M of the sludge drying bed in the operation manual compiled by BORDA engineer Phatang Sananikone for the NLM DEWATS, it is assumed by the author that O&M is required. Wet sludge is typically discharged from the settler into the sludge drying bed to a depth of 200-300mm. The material in the bed is then allowed to percolate through underlying layers until it is discharged into the final collection shaft. After percolation and evaporation has dried out the sludge, the dried sludge is then removed with spades or other appropriate equipment. The dried sludge is transported to a landfill approximately 40km from the NLM site.

3.4.4. Pump

The pump at the outlet chamber of the HFCW is assumed to have an operating lifespan of 20 years (Kirk and Dell'Isola, 1995). Maintenance regarding the pump according to Sananikone requires weekly inspections to ensure the pump is functioning properly. Calculations regarding the pump daily operating hours and electricity consumption during operation is presented in **Chapter 5** of this dissertation.

3.5. Summary

One of the sanitation solutions identified by the eThekwini Municipality for current and future housing developments is the Decentralised Wastewater Treatment System. A pilot project through a partnership with the eThekwini Municipality, BORDA and the Pollution Research Group has allowed for further research into the application of DEWATS in the city of Durban. The case study presented in this chapter provides details regarding the Newlands Mashu DEWATS site. The wide scale implementation of DEWATS for future and existing housing projects will have an impact on the environment throughout its life cycle. The study presented in this dissertation aims to quantify the environmental impacts associated with the NLM DEWATS and to provide insight to relevant decision makers and planners.

CHAPTER 4: GENERAL METHODOLOGY AND GOAL AND SCOPE DEFINITION

4.1.Introduction

This chapter presents the general methodological steps used in this study as well as the goal and scope definition. The methodology of a study includes the formation of a number of detailed and structured steps in order to carry out and achieve the aims and objectives of the study. A detailed literature review was done in **Chapter 2** in order to develop a further understanding of the study from an environmental and technical perspective. The focus of the literature review was mainly on decentralised wastewater treatment and environmental life cycle assessment. The ISO 14040 and 14044 international standards were used to carry out the LCA study. This chapter also discusses a few Life Cycle Assessment (LCA) software packages that are often used in sanitation system related LCA studies. Lastly, the goal and scope definition of the study was outlined.

4.2.Literature Review

The literature review was done in order to gain a better understanding of the study and was divided into four main sections. The first section introduces the reader to the importance of sanitation. The importance of sanitation from a health, economic, social and environmental perspective was presented. The environmental aspect of sanitation was further elaborated since the focus of this study is on the environmental performance of a sanitation system. The second section discussed in the literature review for this study was provided to develop a better understanding of the sanitation situation in South Africa. The governance and policies regarding sanitation as well as current sanitation service levels and backlogs were provided to show the context of the local sanitation situation. The next section included a general overview of sanitation systems and thereafter decentralised wastewater treatment systems. The general overview of sanitation systems provides the reader with an overview of the typical product materials that comprise a sanitation system as well as typical functional groups in sanitation systems. Since the focus of this study was on decentralised wastewater treatment systems in a local context, further information regarding DEWATS in developing countries was presented. Lastly, since the focus of

this study is on the environmental performance of DEWATS, environmental life cycle assessment was discussed in detail. The overall structure of LCA and the applicable 14000 ISO series standards were discussed. The chapter concludes with a specific focus on the application of LCA on sanitation systems as well as LCA in a South African context.

In recent times, a number of LCA studies have been applied in the context of developing countries (Gallego-Schmid and Tarpani, 2019). With respect to application of LCA for sanitation systems in developing countries and DEWATS, relevant literature was obtained from a few databases. The sources of information were gathered from platforms such as SpringerLink, Scopus, ScienceDirect and ResearchGate. In order to refine the search for relevant case studies, key words such as life cycle assessment, sanitation, DEWATS, wastewater treatment were used to name a few.

4.2.1. Life Cycle Assessment Tools

A number of different modelling tools and software packages are available to undertake an LCA. In a recent review of wastewater related LCA studies in developing countries (Gallego-Schmid and Tarpani, 2019), less than half of the LCA studies performed made use of commercial software packages. The introduction of available freeware (e.g. OpenLCA) is likely to have a positive influence on wastewater-related LCAs in the years to come. This section looks briefly at some of the most commonly used software packages used to perform environmental LCA in the field of wastewater treatment technologies. LCA software packages enter and vanish from the market at each and every year, however, two commercial software packages (SimaPro and GaBi) have dominated the market share since the inception of LCA and LCA software development. SimaPro and GaBi offer software packages that meet the needs of most LCA practitioners (Curran, 2008) and hence are the focus of the sections that follow.

4.2.2. SimaPro

SimaPro is a software package that was first developed and released in 1990 by PRé Consultants in the Netherlands (Pre-Sustainability, 2016). The software package consists of a user interface for modelling the product system, databases for unit processes, impact assessment databases that are set up to support many life cycle impact assessment methodologies and lastly a calculator which performs calculations based on the data from the databases and the way the product system has been modelled in the user interface. The software package is set up with various databases and libraries. These libraries contain data for the most common processes and materials such as transportation, electricity production and so forth. A popular library amongst LCA practitioners and LCA software packages is the Ecoinvent database which consists of thousands of inventory data sets and is available on SimaPro. SimaPro calculates the product system in a matrix inversion and runs through thousands of processes in a single efficient step. SimaPro is thus able to deal with a significant number of unit processes in one calculation. The individual contribution of unit processes can only be assessed at the end of the calculation (Curran, 2008). SimaPro has been used to undertake several LCA studies to determine the environmental performance of decentralised wastewater treatment technologies (Lopsik, 2013, Machado et al., 2007, Opher and Friedler, 2016). Most importantly though, SimaPro has been implemented to determine the environmental performance of DEWATS.

4.2.3. GaBi

GaBi is an LCA software package developed by thinkstep. The programme was initially released in 1993 with the purpose of providing users with the ability to undertake LCAs, energy efficiency analysis and sustainability reporting. GaBi has an intuitive user-friendly interface that is based around plans, processes and flows. Plans represent the life cycle that is being analysed, processes are placed on the plan to represent the actual steps occurring in the plan and flows connect the processes and represent the energy and materials moving around in the system (GaBi, 2020). **Figure 29** demonstrates the user interface as seen in GaBi. The life cycle of a paper clip is being modelled and is the “plan”, the various processes are shown linked by flows.

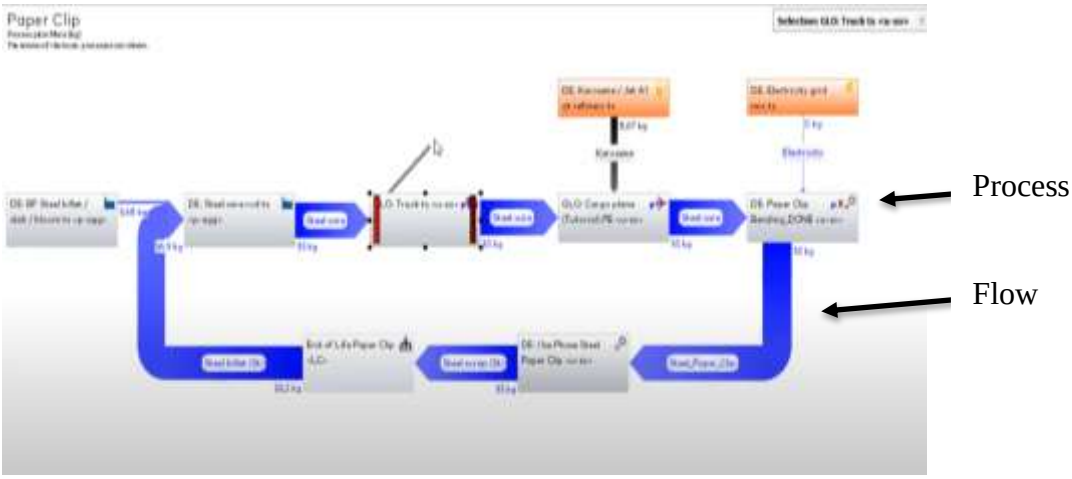

Figure 29: Example of GaBi user interface

GaBi uses a sequential calculation algorithm that jumps from one process to another to scale the process according to its input to the overall LCA system (Curran, 2008). In GaBi, users manually build a system of connected processes. Calculations or done in a stepwise fashion and users obtain feedback on individual modelling steps, developing modelled parts, placing them together part by part (Curran, 2008). This software package has been used for a number of LCA studies in the field of off-grid sanitation technologies (Flores et al., 2009, Frances, 2012, Shi et al., 2018) and of particular importance to this study, it has been applied to determine the environmental performance of DEWATS (Frances, 2012).

Both SimaPro and GaBi would be appropriate tools to perform the LCA for this study since both software packages have been successfully used to undertake LCA studies of a similar nature. Herrmann & Moltesen (2014) looked at both SimaPro and GaBi software to determine if the use of a leading software package could influence the results of an LCA study. The study found that in many instances, the software package produced similar results, however, significant differences were found at both the inventory and impact assessment level (Herrmann and Moltesen, 2015). The differences were linked to the differences in the databases of SimaPro and GaBi. However, for an ordinary or even skilled LCA user it is unlikely that they would have the capability to detect the potential error in the database. SimaPro was selected for use in this study since it has been successfully used in similar studies, it includes large inventory and impact assessment databases required for the analysis and since a

license is readily available to post graduate engineering students at the University of KwaZulu-Natal.

4.4. Goal of the Study

The primary goal of this study is to establish environmental information regarding the Newlands Mashu BORDA DEWATS plant. Furthermore, the study looks at the use of conventional flush toilets with typical sewerage conveyance and low flush toilets with typical sewerage conveyance. The specific objectives of this study are described as:

- To establish environmental information regarding the wastewater treatment systems considered in this study and underline potential areas of improvement based on their environmental performance.
- To provide recommendations for the improvement of the environmental performance of the decentralised wastewater treatment systems included in this study.

It is formally a requirement in the goal and scope definition procedure to mention the purpose of the study and the intended audience. Currently in South Africa there is a large sanitation backlog. Many South African's are exposed to unsafe, undignified and unimproved sanitation practices. More specifically, the situation of sanitation in peri-urban slums and informal settlements is a major issue in South Africa. As mentioned previously in **Section 2.3**, sanitation provision is a deeply political issue and the lack of adequate sanitation has often lead to the increase in service delivery protests (Morudu, 2017, Tapela, 2015). The eThekwini Municipality has highlighted DEWATS as a potential solution for addressing the sanitation backlog in informal settlements as well as support planning for greenfield housing projects (PRG, 2015). However, in order to improve the status of sanitation in informal settlements in a sustainable manner, it is also important to consider the environmental burden of available alternative technologies. This LCA study is intended to provide detailed environmental information regarding the implementation of the BORDA DEWATS technology in the context of eThekwini Municipality. This information should assist water and sanitation technicians, professionals and decision-makers (***intended audience***) in reducing the environmental footprint of the technologies considered in this thesis.

4.5. Scope Definition

It is important in the scope definition of an LCA study that enough detail is provided and is consistent with the intended application of the study (ISO, 2006b). The systems that are investigated in this study include:

A. The existing Newlands Mashu DEWATS system, assuming a conventional 8 litre toilet flush at the household and including the sewer network that conveys wastewater from 84 households to the treatment plant and the treatment plant itself.
B. The Newlands Mashu DEWATS system, assuming a low flush 2 litre toilet flush at the household and including the sewer network that conveys wastewater from 84 households to the treatment plant and the treatment plant itself. **System B** chosen after obtaining the results for **System A** as a typical improvement in the current sanitation landscape.
C. The Newlands Mashu DEWATS system infrastructure and operation, excluding the sewer network and domestic flush water. **System C** was chosen in order to highlight and identify areas for improvement within the treatment plant itself, excluding the sewer network.

The ***system function*** is to treat wastewater to standards that are acceptable according to discharge standards. For this study, the South African Guidelines for agricultural purposes are used, more specifically for irrigation in agriculture (Department of Water Affairs and Forestry, 1996, Department of Water Affairs and Forestry, 2004) . The discharge standards typically differ from country to country and also depend on where the final effluent is intended for discharge.

The ***System Boundaries*** for the systems considered in this study are shown in **Figure 30** overleaf. **Figure 30** shows the simplified processes involved in each system for this study, more detailed system boundary diagrams are shown in **Figure's 32**, **33** & **34** in **Chapter 5**. The detailed diagrams show the processes that are included in the LCA study. It is important to note that the end-of-life (demolition) phase for this study has been neglected since its contribution has been considered negligible in literature (Machado et al., 2007).

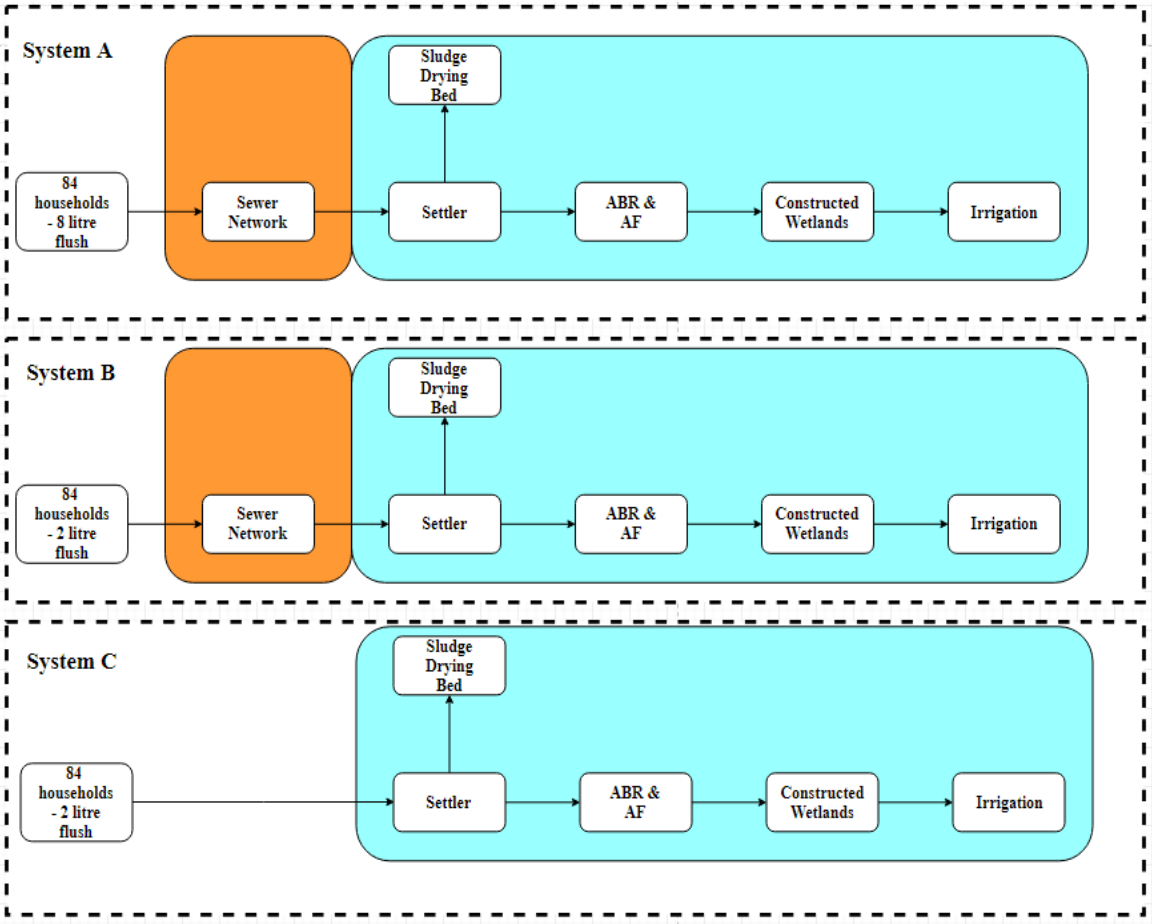

Figure 30: Systems considered in the LCA study

System A as seen in **Figure 32** is the base scenario that is in investigated in this study and includes the existing Newlands Mashu plant and the associated sewer network. After performing an LCA for **System A**, a potential improvement scenario was suggested by replacing conventional flushing toilets with low flushing toilets. **System B** represents the low flush scenario. Calculations for the wastewater volumes are shown in **Table 9** and **Table 10** that distinguish between the studied systems. Lastly, an LCA was performed for **System C** in order to determine the major contributors within the treatment plant itself excluding the sewer network.

The functional unit for this study is defined as the provision of sanitation services for 84 low to middle income households in Newlands, KwaZulu-Natal over a period of 20 years. Since the quality of the wastewater treated in all systems is considered to be the same (the same treatment modules are considered for all three systems), a volumetric functional unit is suitable in this study. The planning data for the functional unit in each system is shown in **Table 9** and **Table 10**.

Table 9: Functional unit planning data for System A and System C

System A & C Planning Data

	No of Households	People per household	Urination Frequency	Defecation Frequency	Flushes per person per day	Volume per flush	Urine Produced per person	Faeces Produced per person	Black water portion	Greywater portion
Value	84	5	2	1	3	8	1,5	0,15	24	76
Unit						litre	kg/c/d	kg/c/d	%	%
Reference	BORDA	BORDA	*Assumption	*Assumption	*Assumption	CSIR	Remy and Jekel, 2008	Remy and Jekel, 2008	BORDA	BORDA

	Period of Analysis	Urine Produced	Faeces produced per day	Domestic Flushwater produced per day	Greywater produced per day	Total Wastewater	Measured average daily flow
Value	20	630	63	8760	27740	37193	35900
Unit	year	kg/d	kg/d	litre/d	litre/d	litre/d	litre/d
Reference	NA	Calculation	Calculation	Calculation	Calculation	Calculation	- Pillay et al, 2013

Shown above in **Table 9** is the planning data for **System A** and **System C**. As mentioned previously, the functional unit is based on the provision of sanitation services for 84 households. It is important to note the estimation of water demand is based on the assumption that a person urinated twice at their homes each day and had one excrement each day. Gao et al., (2016) used the assumption that each person urinated four times per day and had an excrement once per day. However, in this instance, this estimation may be higher than expected since it does not account for the fact that people may urinate or defecate at their place of work, at school, or somewhere other than their homes. A flush volume of 8 litres was used (South African Council for Scientific Industrial Research, 2000). Moreover, the portion of blackwater and greywater produced was based on estimations by BORDA engineers. The calculated total wastewater reaching the NLM DEWATS in **System A** and **System C** is 37193 litres which is relatively close to the average daily measured flow of 35900 litres per day obtained through studies by Pillay et al., (2012).

Table 10: Functional unit planning data for System B

System B Planning Data

	No of Households	People per household	Urination Frequency	Defecation Frequency	Flushes per person per day	Volume per flush	Urine Produced per person	Faeces Produced per person	Black water portion	Greywater portion
Value	84	5	2	1	3	2	1,5	0,15	7%	93%
Unit						litre	kg/c/d	kg/c/d	%	%
Reference	BORDA	BORDA	*Assumption	*Assumption	*Assumption	Envirosan low flush	Remy and Jekel, 2008	Remy and Jekel, 2008	*Assumption	*Assumption

	Period of Analysis	Urine Produced	Faeces produced per day	Domestic Flushwater produced per day	Greywater produced per day	Total Wastewater	Measured average daily flow
Value	20	630	63	2190	27740	30623	35900
Unit	year	kg/d	kg/d	litre/d	litre/d	litre/d	litre/d
Reference	NA	Calculation	Calculation	Calculation	Calculation	Calculation	- Pillay et al, 2013

Shown above in **Table 10** is the planning data for **System B**. The primary difference between **System A** and **System B** is the volume per flush assumed. In **System B**, it was assumed that a 2-litre flush system was used. Domestic flushwater was reduced from 8760 litres per day to 2190 litres per day, whilst greywater was assumed to be the same in all systems. The total wastewater produced in this low flush scenario (**System B**) amounts to 30 623 litres per day.

Allocation of environmental burdens for the NLM DEWATS system results in a number of outputs including treated wastewater, activated sludge and dried sludge. Allocation is therefore required in order to define the life cycle inventory. Since the inception of LCA allocation has been a major issue and consensus on a how to deal with multifunctional processes has not been reached (Luo et al., 2009). Since there is no clear solution for allocation, a number of different allocation procedures are available for LCA practitioners. The allocation procedure for this study is based on physical allocation methods, using a partitioning ratio based on mass.

Data requirements for this LCA study consisted of:

- Primary data was obtained through direct measurements of as built drawings for the various treatment plant structures, piping and instrumentation.
- Where primary data was not available, secondary data was established from reliable databases, technical literature and reports.
- Mass and energy balances were used when no direct measurements were available.
- Data regarding maintenance and operation of the NLM DEWATS plant was adopted from a technical report provided by BORDA.
- Data regarding the performance of the NLM DEWATS plant was taken from a technical report (Pillay et al., 2014).
- Data regarding the sewer network discharging into NLM DEWATS was obtained from engineers at eThekwini Municipality.
- In cases were geographical data specific to South Africa was not available, European and global data had to be used.
- Regardless of the improvements made in the field of LCA, the LCA community is unfortunately still burdened with the lack of reproducible data quality results and documentation. In order to confirm to ISO 14040 standards, data quality indicators are required to validate the data. However, the lack of data quality system requirement from ISO has generated a number of quantitative and qualitative approaches for assessing data quality.

Assumptions

The following assumptions have been made regarding the study:

- The plant design life was assumed to be 20 years.
- Materials and infrastructure are assumed to last the full design period and replacement was not required.
- Dried sludge and solid waste are assumed to be transported to a landfill 40km away from the Newlands Mashu site.
- Reinforcing steel drawings and information was not available and hence an estimation of 100kg of reinforcing steel per m^3 of concrete was assumed for heavily reinforced concrete structure, 67kg of reinforcing steel per m^3 of concrete was assumed for lightly reinforced concrete.
- The impact of the transportation of materials to the site for construction have been assumed negligible.
- Concrete sewer manhole depth to invert of 1.5m was assumed for all manholes.
- The dismantling phase was assumed to be negligible.
- The user interface (toilet seat, bowl and cistern) was not included in the analysis.
- A urination frequency of two urination events per person per day at each household was assumed.
- A defecation frequency of one excrement per person per day at each household was assumed.
- Losses due to leakages in sewer pipes and ingress of stormwater into sewerage manholes has not been considered.

Limitations

- Lack of site specific data for South Africa for the production of various construction materials that were used at NLM DEWATS.
- Data for each individual manhole was not available for the pipe network. Sewer manholes are known to vary in depth, however, the assumption that each manhole was identical in height had to be made.

- The PVC-U pipe manufacturer of the sewer network was unknown and hence general data had to be used from a South African manufacturer (DPI Plastics, 2017).

This study will undergo one main ***critical review*** through the examining process (both internal and external) of this dissertation. The publication of this study in accordance with ISO 14040 standards is not possible without an external review process. With regard to ***reporting***, this study is presented in the form of a dissertation and submitted to the University of KwaZulu-Natal.

4.6. Impact Assessment Methodology and Types of Impacts

The LCIA phase follows after the LCI and is the phase of an LCA that quantifies the potential environmental impacts with the use of the life cycle inventory analysis. Simply put, the impact assessment is the phase in which the inputs and outputs of a system are associated with potential environmental impacts and effects. With the use of a functional unit, two systems which perform the same function can be compared in terms of their environmental performance. Impact categories are defined according to environmental pathways referred to as cause- effect chains (see **Figure 31** below). Broadly speaking, there are two main impact categories in LCA, midpoint indicators and endpoint indicators. Midpoint indicators account for the cause which results in potential damages, however, it does not account for the potential damages itself. On the other hand, endpoint indicators are related to damage. The endpoint indicators, shown in **Figure 31** for example, are regarded as environmental concerns including human health, extinction of species and availability of resources for future generations.

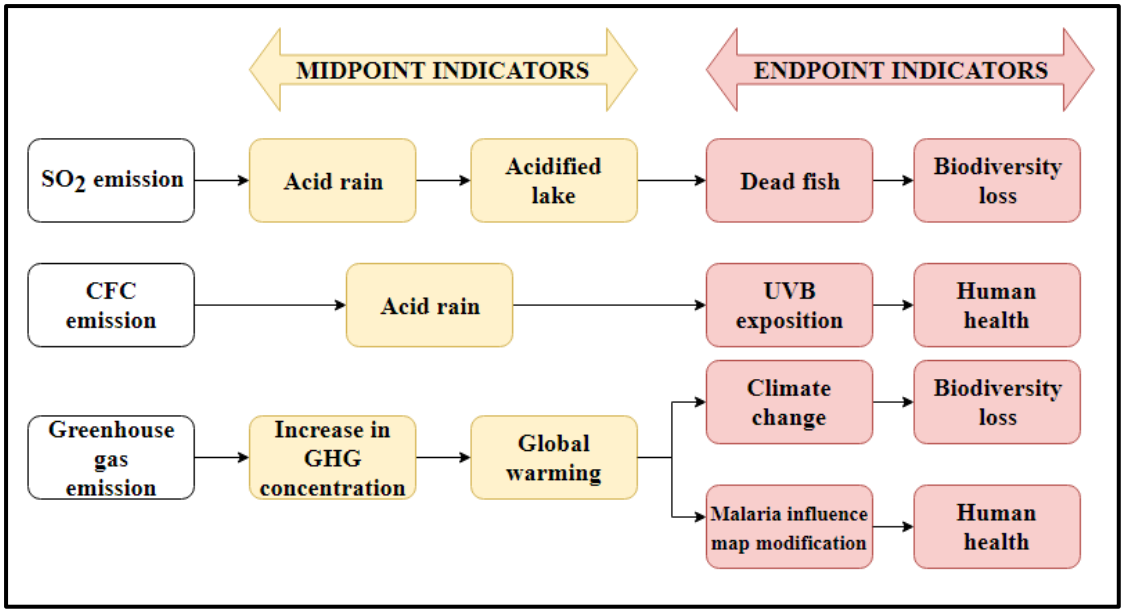

Figure 31: Environmental pathways demonstrating the difference between midpoint and endpoint indicators (Roux et al., 2010)

The LCIA methodology selected for this study is the CML 2001 (baseline) method. This particular methodology is the most frequently used method in WWT-related LCA studies. The impact categories were selected based on their importance to this study. The categories included in this study are:

- Global warming
- Abiotic depletion
- Ozone depletion
- Acidification potential
- Eutrophication potential
- Photochemical oxidation
- Aquatic (fresh water and marine) ecotoxicity
- Terrestrial ecotoxicity
- Human toxicity

4.6.1. Global Warming

In the last 200 years and more significantly in the recent 50 years that have passed, carbon dioxide has been released into the atmosphere in increasing quantities. The source of the emission of carbon dioxide is linked to human activities including the burning of fossil fuels, oil and gas, coal, as well as widespread deforestation

(Houghton, 2009). Radiation from the sun is absorbed into the Earth's atmosphere and some of this radiation is reflected. The increase in concentration of carbon dioxide and other greenhouse gases in the Earth's atmosphere is allowing less radiation to be reflected and more radiation is being absorbed. Global warming is a result of more radiation being absorbed into the atmosphere causing a gradual increase in global temperature. This particular impact category is referred to as global warming potential (GWP) in most LCA methodologies and is measured by the reference unit of kg CO_2 eq.

4.6.2. Ozone Layer Depletion

The ozone layer is a region of concentration of ozone molecules (O_3) in the Earth's atmosphere. This function of the ozone layer is to largely absorb harmful radiation from the sun. Ozone depletion refers to the decrease in concentration of O_3 molecules in the stratosphere due to the introduction ozone depleting gases including chlorofluorocarbons (CFC's) and nitrogen oxides (NO_x). The ozone depleting gases accumulate in the troposphere and drift slowly to the stratosphere where catalytic reaction cycles occur resulting in the destruction of many ozone molecules. Ozone depletion is quantified by ozone depletion potentials (ODP) in most LCA methodologies. The relative measure used for measuring the ozone depletion potential of ozone depleting substances is CFC-11 which has an ODP of 1. The reference unit used to quantify ozone depletion is kg CFC-11eq.

4.6.3. Acidification

Acidification Potential (AP) is a result of the emission of substances into the atmosphere which ultimately is deposited in surface soils and waters. Sulphur dioxide (SO_2) and nitrogen oxides (NO_x) emitted into the atmosphere interact with other components in the air transforming into sulphuric and nitric acids. Acidification has major consequences that damage ecosystems, some common impacts include the reduction of fish stocks and forest dieback. Acidification Potential is quantified relative to a reference unit called kg SO_2 equivalents.

4.6.4. Eutrophication

Eutrophication, or nutrient enrichment, is a consequence of society's industrial, urban and agricultural use of plant nutrients. The term eutrophication is used to define the biological effects of an increase in concentration of plant nutrients – typically nitrogen and phosphorous (Harper, 1992). In a South African context, it has been demonstrated that eutrophication and cyanobacterial blooms are pervasive in water bodies and is of critical concern for water quality (Matthews, 2014). Eutrophication Potential (EP) is measured in terms of a reference unit of kg P equivalents.

4.6.5. Toxicity

Ecotoxicity refers to the impacts of chemical outputs on humans and ecological toxicity. This particular impact category can be further divided into human toxicity, terrestrial ecotoxicity and marine and freshwater ecotoxicity. Impact indicators for this category are typically expressed using 1,4-dichlorobenzene equivalents (1,4-DB eq.).

4.6.6. Photochemical Oxidation

Photochemical oxidants typically indicate the net oxidizing ability of the ambient air. The primary photochemical oxidant is ozone (O_3), accounting for approximately 90 per cent of the oxidant pool. Other potential photochemical oxidants of concern include "nascent oxygen (O), excited molecular oxygen (O_2), peroxyl nitrate (PAN), peroxy-propinol nitrate (PPN), peroxy-butyl nitrate (PBN), nitrogen dioxide (NO_2), hydrogen peroxide (H_2O_2), and alkyl nitrate" (Peavy et al., 1985). The source of oxidants of concern originates from the upper atmosphere as a result of solar radiation whereby small concentrations of ozone gas diffuses downwards. The health effects resulting from photochemical oxidants, amongst many others, include shortness of breath, coughing, airway constriction and has been well recorded in literature (Rowe et al., 1983).

4.6.7. Abiotic Depletion

The impact category of abiotic depletion is related to human health and the ecosystem and how it is impacted by the extraction of abiotic resources including minerals, fossil

fuels, metals and water (Singh et al., 2018). This particular impact category in LCA has been disputed because the problem may be defined in a multitude of ways and since there is no scientifically "correct" means to derive characterisation factors (Van Oers and Guinée, 2016). For this study, the resources of concern are fossil fuels, metals, and water depletion. However, there are two separate impact categories considered, one is abiotic depletion and the other is abiotic depletion of fossil fuels. The former mentioned impact category considers abiotic depletion collectively whilst the latter considers only the depletion of fossil fuels.

4.7. Summary

The chapter provided the general methodology, goal and scope definition. The information presented in this chapter detailed the first phase of an LCA, known as the *Goal and Scope* of the LCA study. The system functions, system boundaries, functional unit, allocation procedures, data requirements, assumptions, limitations and further information were presented.

CHAPTER 5: LIFE CYCLE INVENTORY

5.1. Introduction

The life cycle inventory phase of the LCA specifies the processes required in the production, usage and eventual disposal of a product. It involves data collection and calculations in order to quantify the relevant inputs and outputs of the product systems considered. The process of collecting data began with constructing process flow diagrams for the systems investigated. The process flow diagrams show the important material and energy flows within the sub-processes considered in each system**. Figure 30** previously presented in **Chapter 4** provides an overview of the processes considered in the three systems that are being investigated. More specific system boundaries for each system is shown in **Figures 32, 33 & 34** including both construction and operation phases.

5.2. Data Collection for Inventory

Once the process flow diagrams were compiled, the quantities of the materials used for the construction of the plant were obtained through construction drawings provided by BORDA. With the use of the drawings it was possible to perform volume calculations for the materials used in construction including concrete, brick, cast iron manholes, sand and gravel, reinforcing steel and other materials used for construction. For certain components, manufacturer specification sheets were used to obtain material quantities.

Operation and maintenance data of the plant was obtained through two main sources. The main source of information came from an operation and maintenance guideline (Sananikone, 2012). The data was compiled and computed with the use of Microsoft Excel in spreadsheet format.

Finally, once all data regarding the construction and operation of the plant was compiled, the data was then related in terms of the functional unit. The summarised and related inventory data was then entered into the SimaPro software. The procurement of data for this LCA was the most time consuming aspect of the project

and required communication with BORDA engineers, engineers from eThekwini Municipality and researchers involved with the Newlands Mashu DEWATS plant.

5.3. System A

This section describes the methods of data collection used and the scope of work that is included in the LCA for **System A**. The system boundaries for this system is clearly shown in **Figure 32** and details the process and sub-processes that are included as well as those that are excluded from this study. **System A** process inputs are shown in **Table 11.**

5.3.1. System A – Construction Phase

The construction phase for **System A** can consists of both the current Newlands Mashu DEWATS plant (described earlier in Chapter 3) and the sewer network that conveys wastewater from 84 households to the plant at 71 John Dory Drive in Newlands. The passages that follow describe the procurement of data and how data was prepared for modelling in SimaPro.

The sewer network conveying wastewater to the DEWATS system comprised of four main components namely sewer pipes (PVC-U), concrete manholes, reinforcing steel and cast iron manhole covers. A scaled drawing of the pipe network was provided by the eThekwini Municipality (see **Appendix F**). From the scaled drawing it was possible to obtain pipe lengths and pipe diameters. Pipe manufacturer specification sheets provide mass per unit length data for a given pipe material, diameter and class. With the use of the pipe manufacturer information it was then possible to calculate, through basic multiplication, the mass of pipe materials required for the sewer construction. Typical detail drawings provided by the city engineers for typical sewer manholes were used for quantifying materials used for manhole construction. With the use of the detailed drawings, it was possible to calculate the mass of concrete required per manhole. Due to the lack of individual manhole data, the depth to invert of each manhole was assumed to be 1.5 m. Once the mass of concrete associated with a single manhole was calculated, the amount of reinforcing steel per manhole was estimated. The estimation of reinforcing steel was assumed to be 74 kg/m^3 of concrete. The mass per cast iron manhole cover was calculated from the typical detail

drawings. Once the mass of individual materials associated with a single manhole was calculated, the total amount of materials was obtained by multiplying by the total amount of sewer manholes in the sewer network.

The Newlands Mashu DEWATS plant is comprised of nine main components namely PVC-U sewer pipes, HDPE pipes, concrete, reinforcing steel, cast iron manhole covers, bricks, LLDPE (Jojo Tank), sand and gravel. Detailed drawings of the plant components were provided by BORDA engineers which allowed for the calculation and quantification of concrete, cast iron manholes, PVC-U and HDPE pipes and bricks. Similar to the sewer network, the pipe masses were obtained using mass per length data provided by manufacturer data sheets. The concrete components at the plant included the ABR unit, the sludge drying bed, splitter boxes, the siphon chamber, manholes and distribution chambers and base for the Jojo tank. For all of the aforementioned concrete components except for the Jojo tank base, detailed drawings were used to quantify the volume of concrete and consequently the mass. The Jojo tank base was measured on site. Consistent with the assumptions made in the sewer network, reinforcing steel was assumed to be 74 kg/m^3 of concrete in all concrete components. Brick was used to construct the splitter boxes, HFCW outlet chamber, and was required for the construction of both horizontal and vertical flow constructed wetlands. Detailed drawings were used to quantify the amount of brick in the aforementioned components. The mass of the LLDPE ("Jojo" tank) tank was obtained through manufacturer specifications. Lastly sand and gravel was required in large volumes for the construction of both the vertical and horizontal flow constructed wetlands as well as the sludge drying bed. The current design of both the vertical and horizontal flow constructed wetlands caters only for one third of the entire design flow. The size of the ponds considered for this study was considered to be three times the size of the ponds that currently exist at Newlands Mashu DEWATS plant. The quantity of sand and gravel was also obtained through the use of detailed design drawings and calculations.

5.3.2. System A – Operation Phase

For the treatment of wastewater from 84 households at the Newlands Mashu DEWATS for the period investigated, the primary inputs considered included, potable water, energy consumed by a pump and transportation required for sludge and solid waste management. The pump considered in **System A** is a pump that delivers the final effluent from the outlet chamber of the HFCW to a Jojo Tank. The power requirements of the pump were obtained from the manufacturers specifications and calculations were performed regarding the estimated daily operational times. The manufacturer specifications were compared with calculations shown in Section 5. 6. Fats, oils, grease and solid waste are removed weekly from the plant and transported to a local municipal landfill site. Desludging occurs on a yearly basis. Dried sludge is also transported to the local municipal landfill site. Lastly, the transportation of the initial seeding sludge was also included in this analysis. Information regarding the seeding process was obtained from a technical report (Pillay et al., 2014). Domestic tap water is also included as an input for the operational phase. Domestic tap water is used to convey human excreta to the NLM DEWATS plant. The consumption of domestic tap water for **System A** was based on a 8 litre toilet flush.

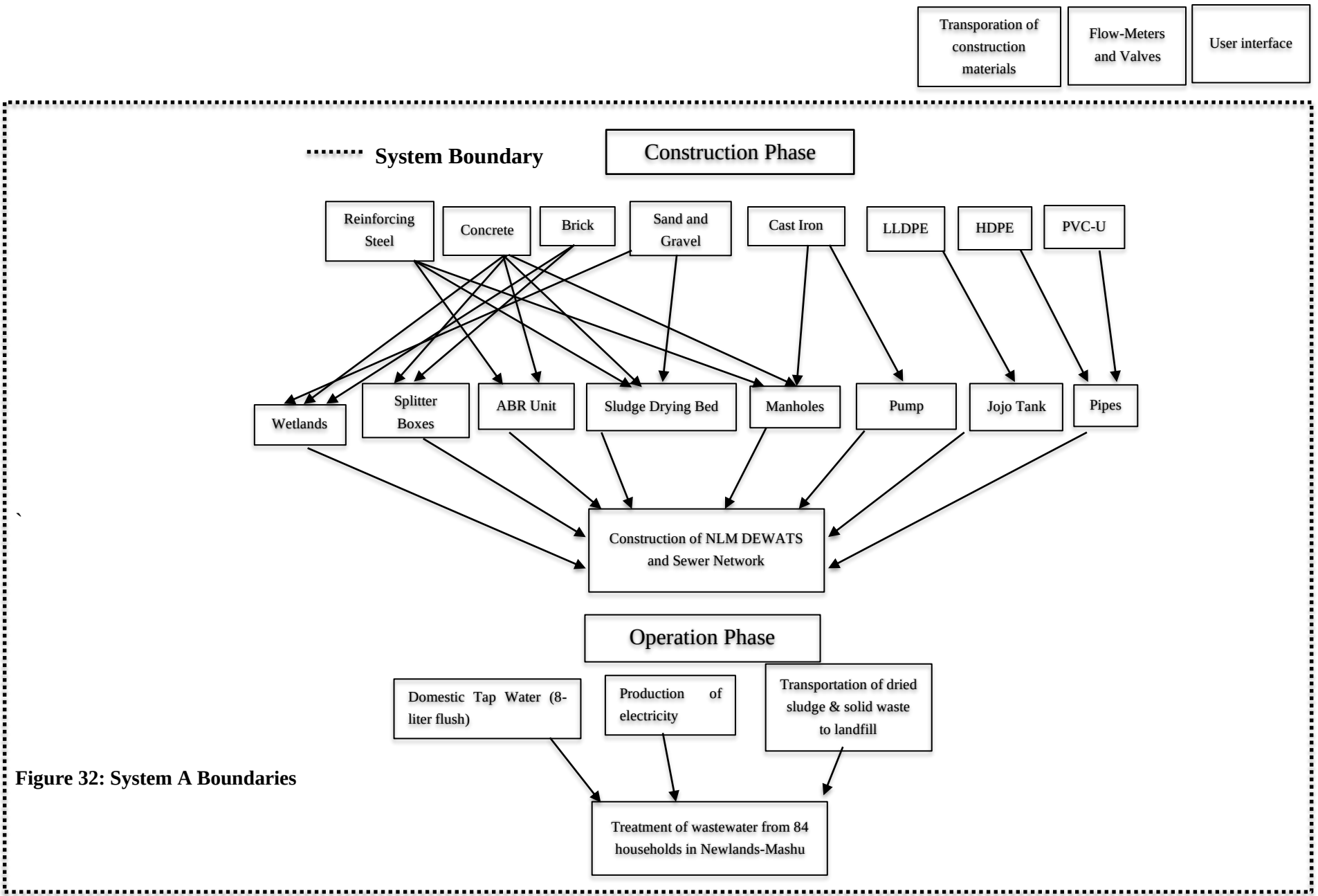

Figure 32: System A Boundaries

Table 11: Inventory Table for System A

UNIVERSITY OF KWAZULU-NATAL INYUVESI YAKWAZULU-NATALI	**System A "Base Scenario"**				
Input Description	**SimaPro database item name**	**Input from Technosphere**	**Inputs from nature**	**Units**	**Value**
Electricity					
Electricity	Electricity, high voltage(ZA)|market for|Conseq, U	✓	×	kWh/FU	6,30E-05
Infrastructure					
PVC	Polyvinylchloride, suspension polymerised (RoW) |polyvinylchloride production, suspension polymerisation|Conseq,U	✓	×	kg/FU	1,61E-05
Cast Iron	Cast iron (RoW)| production |Conseq, U	✓	×	kg/FU	5,13E-05
Concrete	Concrete , normal(CH)| unreinforced concrete production, with cement CEM II/B|Conseq, U	✓	×	m^3/FU	5,03E-07
Reinforcing Steel	Reinforcing Steel (RoW)| production | Conseq, U	✓	×	kg/FU	4,49E-05
Bedding sand	Sand	×	✓	kg/FU	1,20E-03
Brick	Clay Brick (RoW)|production|Conseq,U	✓	×	kg/FU	1,13E-04
LLDPE	Polyethylene, low linear density, granulate(RoW)|production|Conseq, U	✓	×	kg/FU	2,47E-07
HDPE Pipe	Polyethylene, High density, granulate(RoW)|production|Conseq, U	✓	×	kg/FU	8,99E-08
Domestic Flushwater					
Domestic Flushwater	Tap water (RoW)|market for|Conseq,U	✓	×	kg/FU	9,83E-01
Transportation					
Diesel	Diesel(RoW)|market for|Conseq,U	✓	×	kg/FU	1,99E-05

5.4. System B

The following section describes the methods of data collection used and the scope of work that is included in the LCA for **System B.** The system boundaries are clearly shown in **Figure 33**. **System B** process inputs are shown in **Table 12.**

5.4.1. System B – Construction Phase

The construction phase of **System B** is identical to **System A**. The construction phase can also be divided into the sewer network construction and the DEWATS construction. As described in **Section 5.3.1**, the data regarding the sewer pipe network was provided by engineers at the eThekwini Municipality. A scaled drawing and a spreadsheet was provided by the municipality in order to quantify the amount of pipe in the network conveying wastewater to the NLM DEWATS plant. Furthermore, typical detail drawings were used to determine the type of material and the quantity of materials used for the construction of the sewer manholes.

The construction of the NLM DEWATS plant consisted of nine main components namely PVC-U sewer pipes, HDPE pipes and geotextile, concrete, reinforcing steel, cast iron manhole covers, bricks, LLDPE (Jojo Tank), sand and gravel. Further information regarding the scope of the construction data is described previously in **Section 5.1.1**

5.4.2. System B – Operation Phase

The operational phase inputs for **System B** are similar to **System A.** There are three inputs into the model namely electricity to power a pump, diesel consumed in order to transport dried sludge and solid wastes to a landfill site and domestic tap water. The power requirements for the pump used on site were obtained from the pump manufacturers specifications and were compared with calculations shown in **Section 5.6.** Calculations were performed to determine the daily operational hours of the pump. Information regarding the frequency of desludging and removal of fats, oils, grease and solid waste was obtained from a BORDA report on operation and maintenance. The consumption of domestic tap water for **System B** is based on a low flush toilet system which consumes only 2 litres of water per flush.

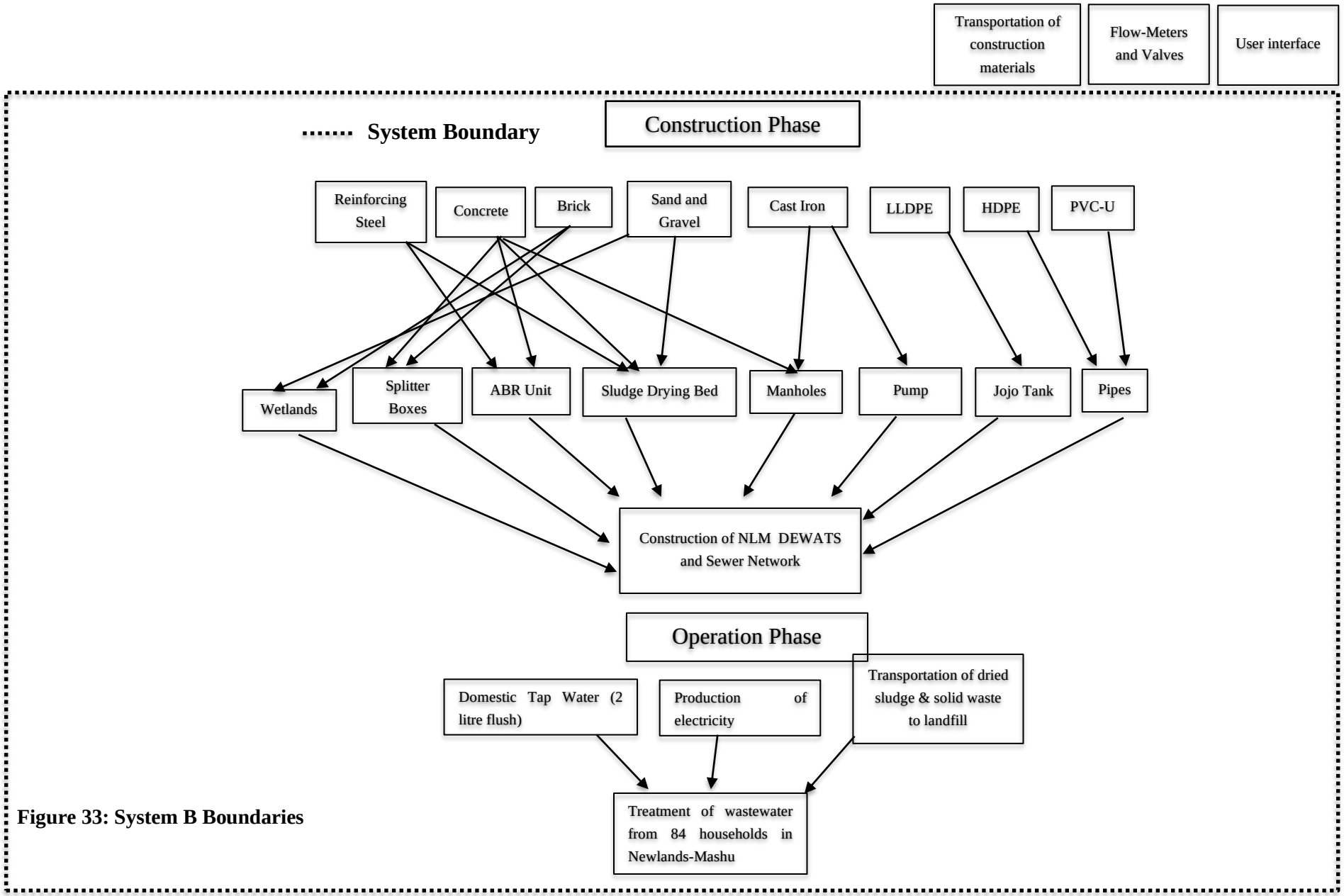

Figure 33: System B Boundaries

Table 12: Inventory Table for System B

System B "Low Flush"					
Input Description	**SimaPro database item name**	**Input from Technosphere**	**Inputs from nature**	**Units**	**Value**
Electricity					
Electricity	Electricity, high voltage(ZA)|market for|Conseq, U	✓	×	kWh/FU	8,31E-05
Infrastructure					
PVC	Polyvinylchloride, suspension polymerised (RoW) |polyvinylchloride production, suspension polymerisation|Conseq,U	✓	×	kg/FU	2,13E-05
Cast Iron	Cast iron (RoW)| production |Conseq, U	✓	×	kg/FU	6,78E-05
Concrete	Concrete , normal(CH)| unreinforced concrete production, with cement CEM II/B|Conseq, U	✓	×	m^3/FU	6,64E-07
Reinforcing Steel	Reinforcing Steel (RoW)| production | Conseq, U	✓	×	kg/FU	5,93E-05
Bedding sand	Sand	×	✓	kg/FU	1,59E-03
Brick	Clay Brick (RoW)|production|Conseq,U	✓	×	kg/FU	1,49E-04
LLDPE	Polyethylene, low linear density, granulate(RoW)|production|Conseq, U	✓	×	kg/FU	3,26E-07
HDPE Pipe	Polyethylene, High density, granulate(RoW)|production|Conseq, U	✓	×	kg/FU	1,19E-07
Domestic Flushwater					
Domestic Flushwater	Tap water (RoW)|market for|Conseq,U	✓	×	kg/FU	9,78E-01
Transportation					
Diesel	Diesel(RoW)|market for|Conseq,U	✓	×	kg/FU	2,63E-05

5.5. System C

The following passages describe the methods of data collection used and the scope of work that is included in the LCA for **System C**. The system boundaries are clearly shown in **Figure 34**. **System C** process inputs are shown in **Table 13.**

5.5.1. System C – Construction Phase

System C, as shown in **Figure 34**, comprises of the NLM DEWATS system excluding the sewer network and potable water supply from the System boundaries. The construction of the NLM DEWATS plant comprises of nine main components namely PVC-U sewer pipes, HDPE pipes and geotextile, concrete, reinforcing steel, cast iron manhole covers, bricks, LLDPE (Jojo Tank), sand and gravel. Further information regarding the scope of the construction data is described previously in **Section 5.1.1**.

5.5.2. System C – Operation Phase

The operation phase for **System C** is identical to both **System A** and **System B.** There are two inputs into the model namely electricity to power a pump and diesel consumed in order to transport dried sludge and solid wastes to a landfill site. The power requirements for the pump used on site were obtained from the pump manufacturers specifications and were compared with calculations shown in **Section 5.6.** Calculations were performed to determine the daily operational hours of the pump. Information regarding the frequency of desludging and removal of fats, oils, grease and solid waste was obtained from a BORDA report on operation and maintenance. Domestic tap water consumption for **System C** was excluded in this scenario. The motivation behind this exclusion is to isolate and investigate the environmental impacts of the NLM DEWATS plant.

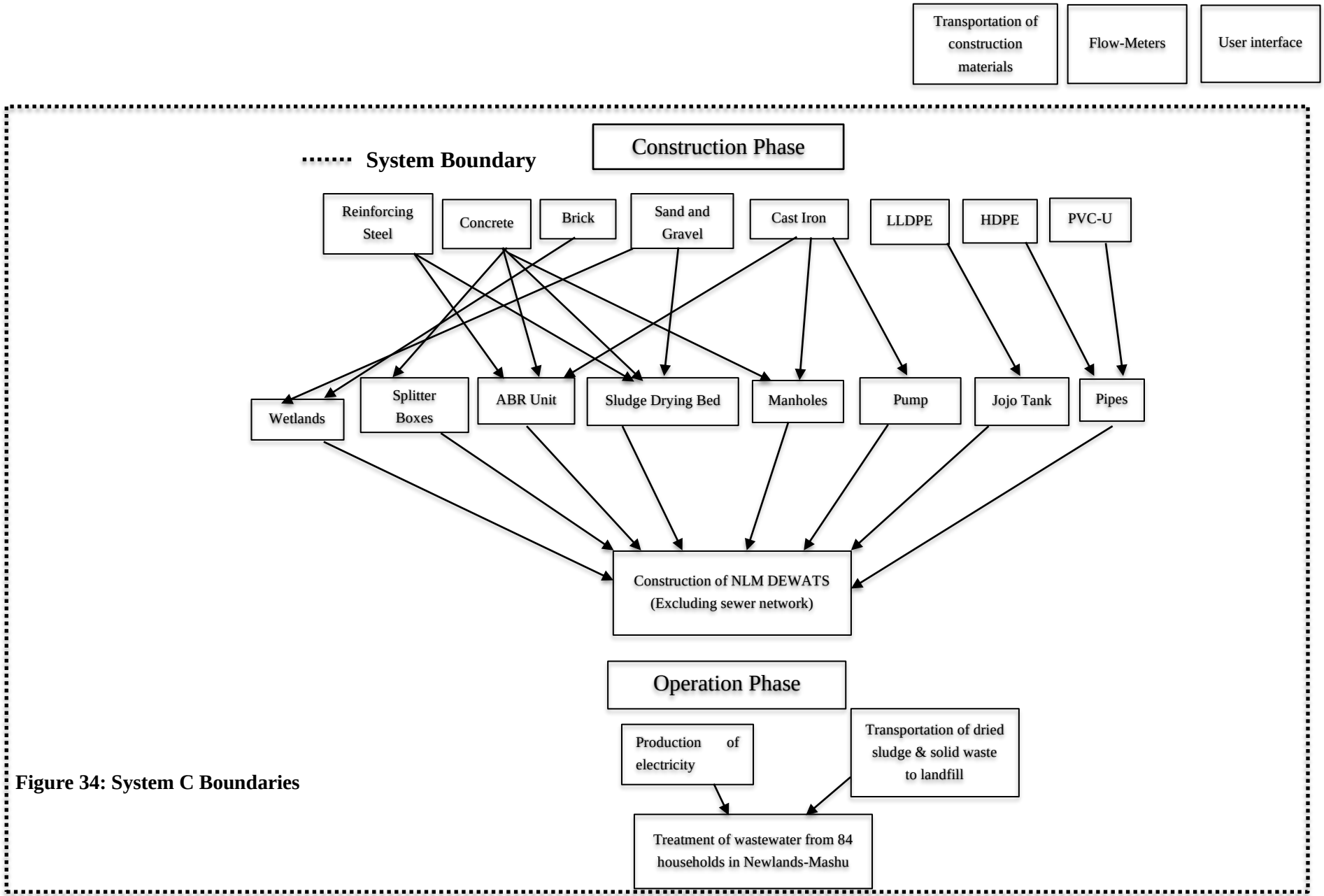

Figure 34: System C Boundaries

Table 13: Inventory Table for System C

System C "DEWATS - excluding sewer network"					
Input Description	**SimaPro database item name**	**Input from Technosphere**	**Inputs from nature**	**Units**	**Value**
Electricity					
Electricity	Electricity, high voltage(ZA)|market for|Conseq, U	✓	×	kWh/FU	6,30E-05
Infrastructure					
PVC	Polyvinylchloride, suspension polymerised (RoW) |polyvinylchloride production, suspension polymerisation|Conseq,U	✓	×	kg/FU	2,41E-06
Cast Iron	Cast iron (RoW)| production |Conseq, U	✓	×	kg/FU	1,21E-05
Concrete	Concrete , normal(CH)| unreinforced concrete production, with cement CEM II/B|Conseq, U	✓	×	m^3/FU	3,04E-07
Reinforcing Steel	Reinforcing Steel (RoW)| production | Conseq, U	✓	×	kg/FU	3,02E-05
Bedding sand	Sand	×	✓	kg/FU	5,47E-04
Brick	Clay Brick (RoW)|production|Conseq,U	✓	×	kg/FU	1,13E-04
LLDPE	Polyethylene, low linear density, granulate(RoW)|production|Conseq, U	✓	×	kg/FU	2,47E-07
HDPE Pipe	Polyethylene, High density, granulate(RoW)|production|Conseq, U	✓	×	kg/FU	8,99E-08
Transportation					
Diesel	Diesel(RoW)|market for|Conseq,U	✓	×	kg/FU	1,99E-05

5.6. Electricity Consumption

The energy inputs for the systems is primarily derived from electricity to power an onsite pump that delivers treated effluent from the outlet sump of the HFCW to a storage tank near the entrance of the NLM site (see **Chapter 3** for more information). The energy requirement for this pump was estimated using the standard pump power shown below in **Equation 1**:

$$P = \frac{\rho * g * Q * H}{\eta} \qquad \text{Equation 1}$$

Where P = power consumption (kW)

ρ = density of wastewater (kg/m^3)

g = gravitational acceleration constant (m/s^2)

Q = pump volumetric discharge rate (m^3/s)

H = Total head required by pump - addition of static and friction head (m)

The density of wastewater in for this study was taken as 1000 kg/m^3, gravitational acceleration constant was taken as 9.81 m/s2. The volumetric flow rate provided by this submersible pump was given as 10 m^3/h (0.0028 m^3/s) as per BORDA specifications. However, since the NLM DEWATS was designed for only one third of the total flow, this figure was multiplied by three and a volumetric flow rate of 30 m^3/h was used. Shown in **Figure 35** is a simplified diagram of the head (energy) required by the pump.

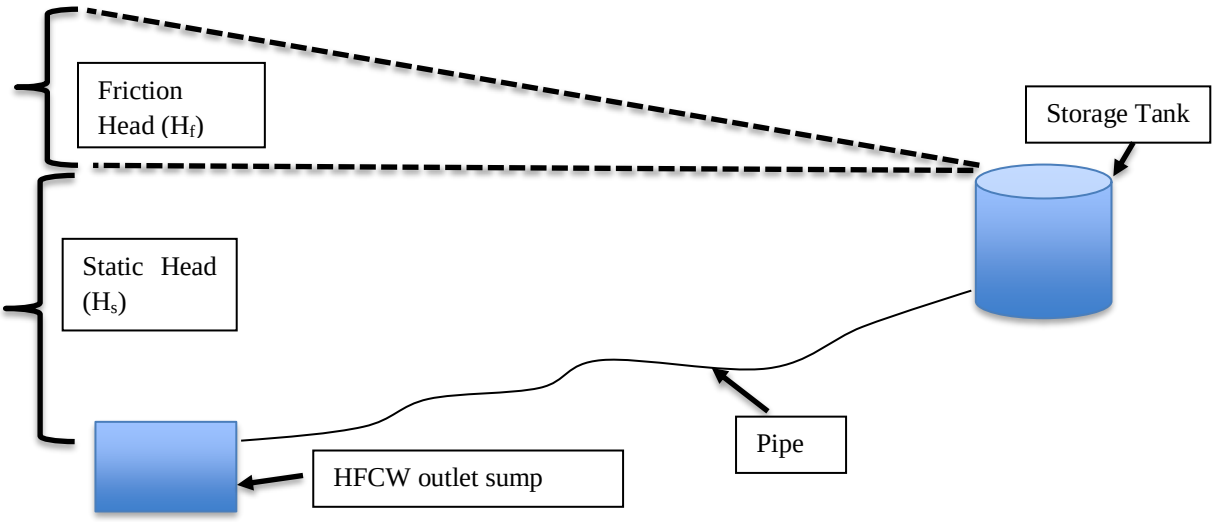

Figure 35: Simplified diagram demonstrating static head and friction head components

The steady flow energy equation and Darcy-Weisbach equation can be used to solve for the head required by the pump. Although the flow into the outlet sump (where the submersible pump is located) is expected to fluctuate throughout the day, the system was analysed as a steady flow system. The reason for considering the pumping as steady flow is since the pump will be activated to switch on at a defined high water level and switch off at a defined low water level. Therefore, regardless of the fluctuation of incoming wastewater flow rate, the pump will be discharging at a constant rate. Pumping is expected to be intermittent and will be expected to operate more frequently during high flows. The static head component is the difference in water surface elevation between the HFCW outlet sump and the storage tank. The frictional head component is given by **Equation 2** shown below. The friction head is described as the energy losses due to friction as the water is delivered from the HFCW outlet sump to the storage tank.

$$H_f = \frac{8 * f * L * Q^2}{\pi^2 * g * D^5} \qquad \text{Equation 2}$$

Where f = pipe friction factor

L = pipe length (m)

Q = volumetric discharge rate (m^3/s)

g = gravitational acceleration constant (m/s^2)

D = pipe inner diameter (m)

The maximum head that the pump was required to deliver water was estimated as 10 m. The final phase in the calculation in order to provide the data in a relevant format for the SimaPro software. Energy requirements in the SimaPro software are measured in units of kilowatt-hour (kWh). This calculation is shown in **Equation 3** below where the power consumption of the pump is multiplied by the daily operating time of the pump.

$$E = P * t \qquad \text{Equation 3}$$

Lastly, the energy consumption per functional unit is determined by dividing the value obtained in Equation 3 by the daily volume of water that passes through the pump as shown in **Equation 4**.

$$E_{fu} = \frac{E}{V} \qquad \text{Equation 4}$$

5.7. Diesel Consumption

At the NLM DEWATS, collection of solid wastes from the system is required in the operation of the plant. Collection of such waste in the eThekwini Municipality is done by truck and the service is facilitated by DSW (DSW, 2016). Around the world, waste management trucks vary from old and poorly maintained trucks to highly technological specialised collection trucks which allow for the compaction of waste compartments. The type of waste management truck typically used by the municipality is shown in **Figure 36.** The vehicle shown in **Figure 36** is the most frequently used waste collection vehicle at the municipality and for this reason it is assumed that a similar type of vehicle is used to collect solid waste at NLM DEWATS.

Figure 36: Typical rear-end loader waste collection truck used by DSW

The type of truck assumed to collect solid waste from NLM DEWATS is a 5 m^3 capacity truck which collects and compacts waste typically sourced from residential areas. For a much larger wastewater treatment facility that may expect much larger volumes of waste, a 19 m^3 collection truck may be more suitable.

A European study undertaken by Larsen et al. (2007) studied the diesel consumption in waste collection under various circumstances. The case considered in this study,

that most closely matched the circumstances at NLM, was residual household waste collection at single-family houses in urban areas. The diesel consumption for this scenario was measured in litres of fuel consumed per tonne (l/tonne) and was found to be an average of 7.5 L/tonne over a distance of 40 km. In order to determine the amount of diesel consumed by the transfer of waste to the landfill site the following calculations were performed.

1. The frequency of collection for the various waste streams is determined. The settler requires removal of solid waste material, fats, oils and grease on a weekly basis. Desludging occurs annually.
2. The mass of material collected is estimated per collection event.
3. The mass of waste generated for the study period (20 years) is estimated and is denoted as M_{20} (in unit of Tonne).
4. The diesel consumed is then calculated using **Equation 5**. A diesel consumption rate of 7.5 L/Tonne is assumed based on studies by Larsen et al (2007).

$$Diesel\ consumed = M_{20} \times 7.5 \qquad \text{Equation 5}$$

5.8. Classification

The second step in any impact assessment is classification. As briefly described in Chapter 2 of this dissertation, classification involves assigning inventory data to previously selected impact categories. The SimaPro software automatically performs this step in this phase of the analysis.

The environmental impacts for each system was modelled on SimaPro in four methods. The first method was to model the **System B**ased on all the individual input materials and energy. The second method used was to model the environmental impacts based on broad input categories such as electricity, infrastructure, domestic water consumption and transportation. The third method used was to analyse the system based on sub-processes within each system. The purpose of analysing the system by sub-process is to compare the relative environmental impacts locally within the systems sub-processes. The final method used was to investigate the contribution of operation and construction. The LCA results of the investigated systems is

illustrated in the form of graph diagrams which demonstrate the relative contributions of particular inputs to the overall environmental loadings for each individual impact category.

5.9. Characterisation and Normalisation

The final mandatory step in the impact assessment is characterisation. Characterisation involves converting LCI results into common units and aggregating the converted results within the same impact category. The amount of a particular material or substance is multiplied by its corresponding characterisation factor in order to quantify the materials contribution to an impact category. For the CML 2001 midpoint assessment method, the characterisation method is described comprehensively in Handbook on Life Cycle Assessment (Guinée, 2002).

The CML methodology was selected for a number of reasons. Firstly, it allows for comparison with other similar studies (Machado et al., 2007, Frances, 2012, Roux et al., 2010). Secondly it has been widely used in LCA, some authors consider it to be the most widely used methodology in LCA (Guinée, 2002). A review of wastewater treatment related LCA studies (Gallego-Schmid and Tarpani, 2019) confirmed that CML was the most commonly used method in developing countries. Moreover, for the studies considered in this literature review (see **Section 2.6.5**), CML includes the impact categories that showed to be most important to decentralised wastewater treatment systems – including Eutrophication, Marine and Freshwater Aquatic Ecotoxicity and Global Warming Potential. The process of characterisation is automatically processed by the SimaPro software which computes the relative contribution with respect to the impact categories reference unit (e.g. kg SO2 equivalents).

The selection of normalisation factors and reference method has shown to have a marked influence on the results and more importantly the interpretation of the results (Aymard and Botta-Genoulaz, 2017). For the selected methodology (CML 2001), normalisation factors were readily available for several European countries as well as global reference factors. Opher and Friedler's (2016) LCA study undertaken for various wastewater treatment and reclamation processes included a normalisation

phase. The location of their study was in Israel wherein country specific normalisation factors were not available. In this instance global normalisation factors were the best option for normalising the results, however, it is not entirely relevant for local conditions (Opher and Friedler, 2016).

Normalisation involves an additional calculation step whereby individual impact categories are divided by a reference value. The reference values selected for use in this study are shown in **Appendix J** - and include the available options for the CML 2001 methodology. The impact indicator results were divided by the 1995 global reference since these would best suited for application in this study since local reference values are not available. The result produced from normalisation are unitless since, taking Eutrophication Potential for example, the amount of kg PO4 equivalent emitted per functional unit by the wastewater treatment system is divided by the total amount of kg PO4 equivalent emitted worldwide in 1995. The purpose of performing this normalisation step is to provide a better understanding of the relative result for each indicator.

5.10. Interpretation

The life cycle interpretation phase of an LCA study contains a number of elements as discussed in **Section 2.6.3**. The interpretation involves the identification of significant issues highlighted in the LCI and LCIA phases, evaluates the completeness of the study includes sensitivity analysis and lastly provides conclusions, limitations and recommendations (ISO, 2006b).

In this study, the provision of sanitation services to 84 households (over an analysis period of 20 years) was analysed with the use of the CML 2001 midpoint method for **Systems A, B** and **C**. In order to achieve the aims set out for this study in the goal and scope, it was necessary to analyse the system based on individual material inputs, by main material input groups, by system processes and lastly by operation and construction. In order to achieve this, the "analyse groups" function was used in the SimaPro software in order to aggregate the relevant inputs. The subsequent section of the life cycle interpretation phase is outlined in **Chapter 7** where further information regarding conclusions and recommendations is provided.

In **Appendix J**, **Table J-1** shows the normalisation factors used for this study. **Figure J-1** shows all the available normalisation factors which vary based on time frame, time horizon and geographic location. **Table J-1** is sorted in descending order to show the most impactful categories from top to bottom. The most significant impact categories in descending order is marine aquatic ecotoxicity, human toxicity, climate change, freshwater aquatic ecotoxicity, acidification, terrestrial ecotoxicity, depletion of abiotic resources, eutrophication potential, photochemical oxidation and lastly stratospheric ozone depletion. Normalisation factors were available for all impact categories used in the CML 2001 midpoint method and were included in this study. According to Huijbregts et al. (2003), the most complete source of normalisation factors is the 1990 set of factors. Moreover, the difference in scores between the 1990 and 1995 factors are within a scale of 1.5. Although the 1995 normalisation factors are 25 years old, these factors are arguably the best selection for normalisation factors for this study since they are the most recently available scores for this methodology and they are the best selection since there are no geographically specific factors available. Since the difference between using 1990 and 1995 normalised factors produces a small change in the final scores, it may be reasonable to assume that the 1995 factors would be reasonably within range of current factors if they were available. However, it must be said that if current factors were available for use, these would most certainly produce a more accurate final result.

5.11. Summary

This chapter presented the life cycle inventory phase of the LCA study. In this chapter, further information regarding the systems investigated in this LCA was provided. For each system, the material and energy inputs for the construction and operation phase was presented. Furthermore, detailed system boundary diagrams and inventory input tables were provided for the systems investigated. The consumption of electricity and diesel was further elaborated to provide the reader with an understanding of how this data was calculated. Lastly, classification, characterisation and life cycle interpretation were discussed. The aforementioned topics are not normally found under the LCI phase of an LCA study, however, they dictate how the LCI information is processed and provides background to the chapter that follows.

CHAPTER 6: RESULTS, DISCUSSION & INTERPRETATION

6.1. Introduction

This chapter presents the results of the LCA study and the initial phase of the Life Cycle Interpretation. The environmental impacts as a result of the construction and operation of the Newlands Mashu DEWATS are discussed. ISO standards specify that the objective of the interpretation phase is to analyse results, explain limitations, provide conclusions and recommendations (ISO, 2006a). The interpretation phase is presented in this chapter as well as in Chapter 7.

6.2. Life Cycle Impact Results

The processed data from the Life Cycle Inventory, including all inputs and outputs of the investigated systems, was used to model the environmental impacts on the SimaPro software. The results of the SimaPro simulations are characterised into a number of impact categories (as previously described in **Section 4.6**). The impact categories are based on the CML baseline impact assessment method. For the systems investigated, the impact assessment score results are initially demonstrated. The impact assessment results are then shown for each system in further detail by showing relative percentage contributions. The percentage contributions are displayed by means of individual material inputs and broad input categories (electricity, infrastructure, transportation, domestic water consumption and discharges) in order to demonstrate the shared contribution of inputs in a particular category for the systems investigated. The inputs are grouped according to their various sub-processes within the **System C**onsidered. This method can demonstrate the contribution of the stages in the wastewater treatment process to various environmental impacts for the systems investigated. Finally, the systems are analysed by construction inputs and operation inputs.

6.2.1. Impact Assessment Results for System A – Current Plant

In order to demonstrate the differences between the studied systems it is important to show and compare the environmental impact scores. Shown in Table 16 is the overall environmental impact scores for **System A**, **B** and **C**. The numbers demonstrate the

fact that the base scenario (**System A**) is the most environmentally burdensome system. **System B** (low flush) results in significantly lower environmental impact scores across all categories. The lesser amount of domestic flushwater required for **System B** is attributed to this reduction in impact scores when comparing **System A** and **System B**. **System C** is also included in **Table 16**, however, it must be noted that a strict comparison is not valid since **System C** does not include the wastewater conveyance process.

Table 14: Comparison between Impact Assessment Results for Systems A, B and C

Impact Category	Units	System A	System B	System C
Abiotic depletion	**kg Sb eq.**	1.42E-08	3.31E-09	1.22E-10
Abiotic depletion (fossil fuels)	**MJ**	1.39E-07	2.57E-08	2.4E-09
Global warming (GWP100a)	**kg CO_2 eq.**	2.35E-07	1.34E-07	1.17E-09
Ozone layer depletion (ODP)	**CFC-11 eq.**	5.60E-09	7.91E-11	6.45E-12
Human toxicity	**kg 1,4-DB eq**	4.63E-08	1.05E-08	5.09E-10
Fresh water aquatic ecotox.	**kg 1,4-DB eq**	3.55E-07	5.93E-08	9.63E-09
Marine aquatic ecotoxicity	**kg 1,4-DB eq**	3.88E-06	6.65E-07	8.92E-08
Terrestrial ecotoxicity	**kg 1,4-DB eq**	4.85E-08	6.12E-09	3.14E-10
Photochemical oxidation	**kg NMVOC eq.**	3.15E-08	1.75E-08	2.11E-10
Acidification	**kg SO_2 eq**	3.42E-08	1.98E-09	1.56E-09
Eutrophication	**kg PO_4^{3-} eq.**	1.30E-06	6.32E-07	5.16E-07

In order to understand the significant influence of domestic water on the studied systems it is important to take note of the relative magnitudes of the scores. Shown in Table 17 is the order of magnitude of **System A** relative to **System B** and **System C**. The values in Table 17 were calculated as per the below example:

Calculation of **System A** abiotic depletion when compared with **System B**.

$$Order\ of\ Difference = \frac{System\ A\ Abiotic\ Depletion}{System\ B\ Abiotic\ Depletion}$$

$$= \frac{1.42E-08}{3.3E-0.9} = 4.30$$

System A, the most environmentally burdensome system, is an average 1.16E+01 larger than **System B** and 1.59E+02 larger than **System C** across all impact categories. When observing the differences between the base scenario (**System A**)

and the low flush scenario (**System B**), the smallest order of difference was for global warming (GWP100a) with 1.76 and the largest difference was ozone layer depletion with 70.82. The order of difference between **System A** and **System C** was calculated in a similar method. The smallest order of difference is eutrophication which is shown as 2.52 and the largest order of difference is also ozone layer depletion at 868.22.

Table 15: Magnitude of differences when compared with the System A (Base Scenario)

Impact Category	Units	System B	System C
Abiotic depletion	**kg Sb eq.**	4.30	116.98
Abiotic depletion (fossil fuels)	**MJ**	5.41	57.74
Global warming (GWP100a)	**kg CO_2 eq.**	1.76	201.29
Ozone layer depletion (ODP)	**CFC-11 eq.**	70.82	868.22
Human toxicity	**kg 1,4-DB eq**	4.42	90.93
Fresh water aquatic ecotox.	**kg 1,4-DB eq**	5.98	36.86
Marine aquatic ecotoxicity	**kg 1,4-DB eq**	5.84	43.49
Terrestrial ecotoxicity	**kg 1,4-DB eq**	7.92	154.47
Photochemical oxidation	**kg NMVOC eq.**	1.80	149.30
Acidification	**kg SO_2 eq**	17.25	21.87
Eutrophication	**kg PO_4^{3-} eq.**	2.06	2.52
Average		1.16E+01	1.59E+02

In summary, the systems appear to be largely influenced by the magnitude of domestic water required for the wastewater treatment process. In order to further understand the relative contribution of inputs and processes for the studied systems, it is important to appropriately group the systems and study the relative contributions. The subsequent sections aim to provide a greater amount of detail for the respective systems.

6.2.2. Impact Assessment Results for System A – Current Plant

The impact assessment results for **System A** is shown for all inputs (**Figure 37**), by main categories (**Figure 38**), by process (**Figure 39**) and lastly by construction and operation (**Figure 40**).

For the impact category of abiotic depletion, the results show (as seen in **Figure 37**) that reinforcing steel is a significant contributor, accounting for 21.56% followed by cast iron which contributes 17.53%. For abiotic depletion (fossil fuels) there is a variety of significant contributors including diesel (6.69%), reinforcing steel (6.72%), cast iron (6.32%), concrete (5.13%), and lastly PVC (4.26%). For global warming potential reinforcing steel accounts for 10.50% followed by cast iron which contributes 10.41% and less significantly concrete accounts for 5.75%. In the human toxicity impact category reinforcing steel (21.39%) and cast iron (19.03%) contribute largely whilst concrete (3.44%) contributes to a lesser extent. For fresh water aquatic ecotoxicity cast iron (13.61%) and reinforcing steel (11.15%) contribute significantly and concrete (3.11%) accounts for a smaller portion of the impacts. Marine aquatic ecotoxicity involves similar contributors to freshwater aquatic ecotoxicity as cast iron (10.13%) and reinforcing steel (8.50%) contribute largely and concrete (2.54%) contributes to a lesser extent. In terrestrial ecotoxicity cast iron contributes 32.38% and to a less significantly reinforcing steel contributes 3.64%. For photochemical oxidation, the significant contributors are shared by reinforcing steel (12.97%), cast iron (12.75%) and concrete (10.81%). For acidification concrete (20.20%) accounts for a large portion in this category, whilst diesel (3.84%) and electricity (3.43%) contribute less significantly.

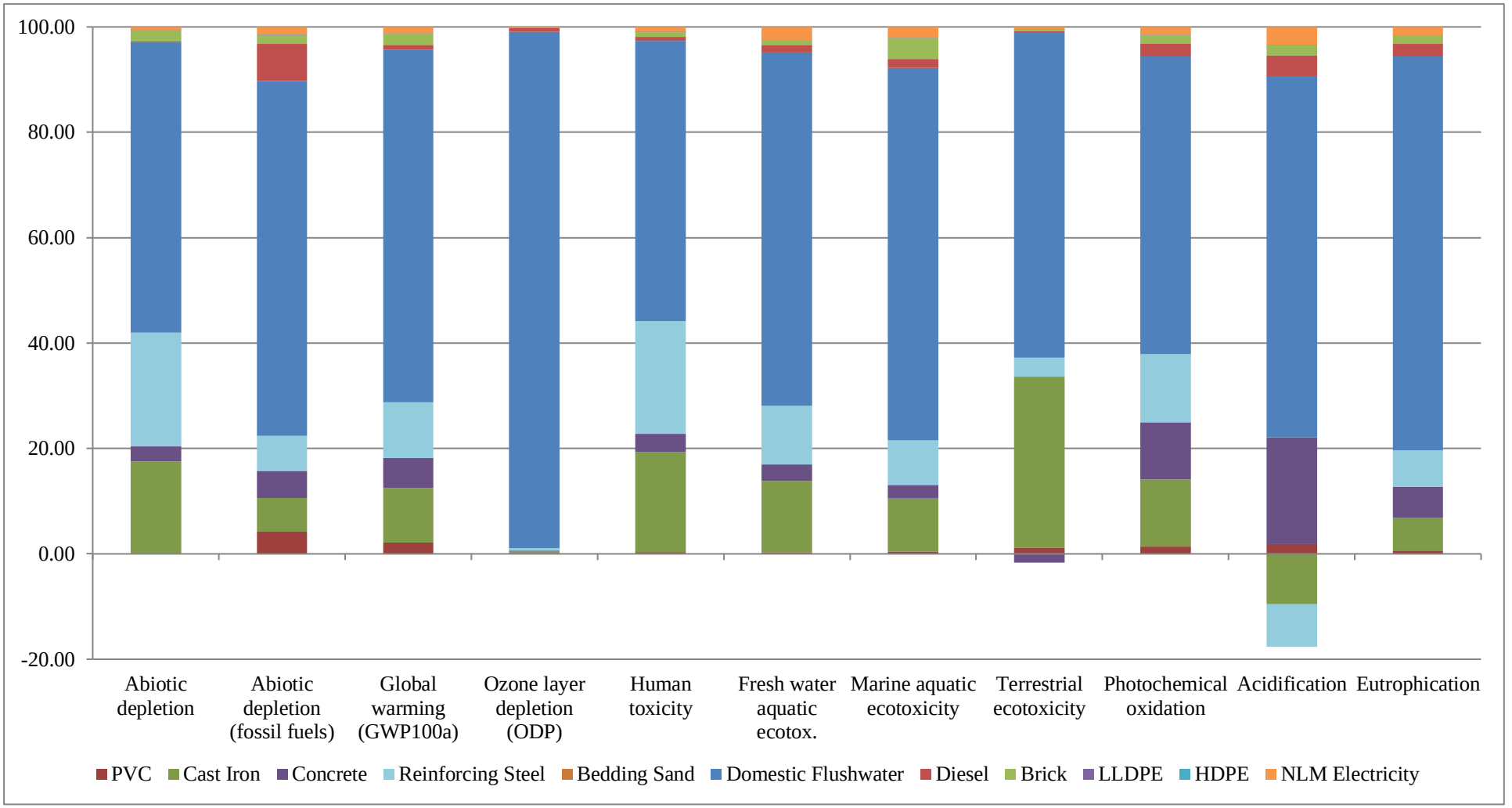

Figure 37: Impact assessment results for all material inputs for System A

It is important to note the positive contribution of both cast iron (-10%) and reinforcing steel (-8%) on acidification. In this case reinforcing steel was modelled using the consequential system model. As a result of the blast furnace that produces the steel, two avoided products including cement clinker and natural gas are shown in the SimaPro dataset. The avoided products from this process result in negative flows across all impact categories, however, only in the acidification impact category are the avoided flows larger than those from the steel furnace. The negative results appear graphically due to these two avoided products. Lastly, for eutrophication, three main construction materials share the bulk of the significant contributions including reinforcing steel (6.93%), cast iron (6.24%) and concrete (5.93%). It is important to also mention, the environmental impacts due to the processes within the wastewater treatment plant were not considered in this scenario. The reason for this omission is to establish which construction material inputs accounted for the largest share of environmental impacts. From the results presented in **Figure 37** it is clear that municipal water used for flushing carries the highest burdens in all categories.

Figure 38 demonstrates the impact assessment of the main input categories for **System A**. It is apparent based on the diagram that domestic flushwater consumption accounts for the largest contribution across most impact categories. Domestic flushwater is the primary contributor to all impact categories except for global warming, photochemical oxidation and eutrophication. The second largest contributor across most impact categories is the infrastructure input group. This input group includes reinforcing steel, cast iron, concrete, brick and thermoplastic materials. Infrastructure contributes significantly to all impact categories except for eutrophication and ozone layer depletion. Discharges were shown to be the major contributor to three impact categories namely eutrophication (96.09%), global warming (66.38%) and photochemical oxidation (68.84). The abovementioned discharges include methane discharges to air from anaerobic digestion as well as nutrient discharge into the environment from incomplete removal of nutrients (amomonia and phosphate). The contribution of electricity and transportation was far less significant than other input groups. The largest contribution from electricity is in the acidification impact category with 4.19% and the largest for transportation is in the abiotic depletion (fossil fuels) impact category contributing 6.84%.

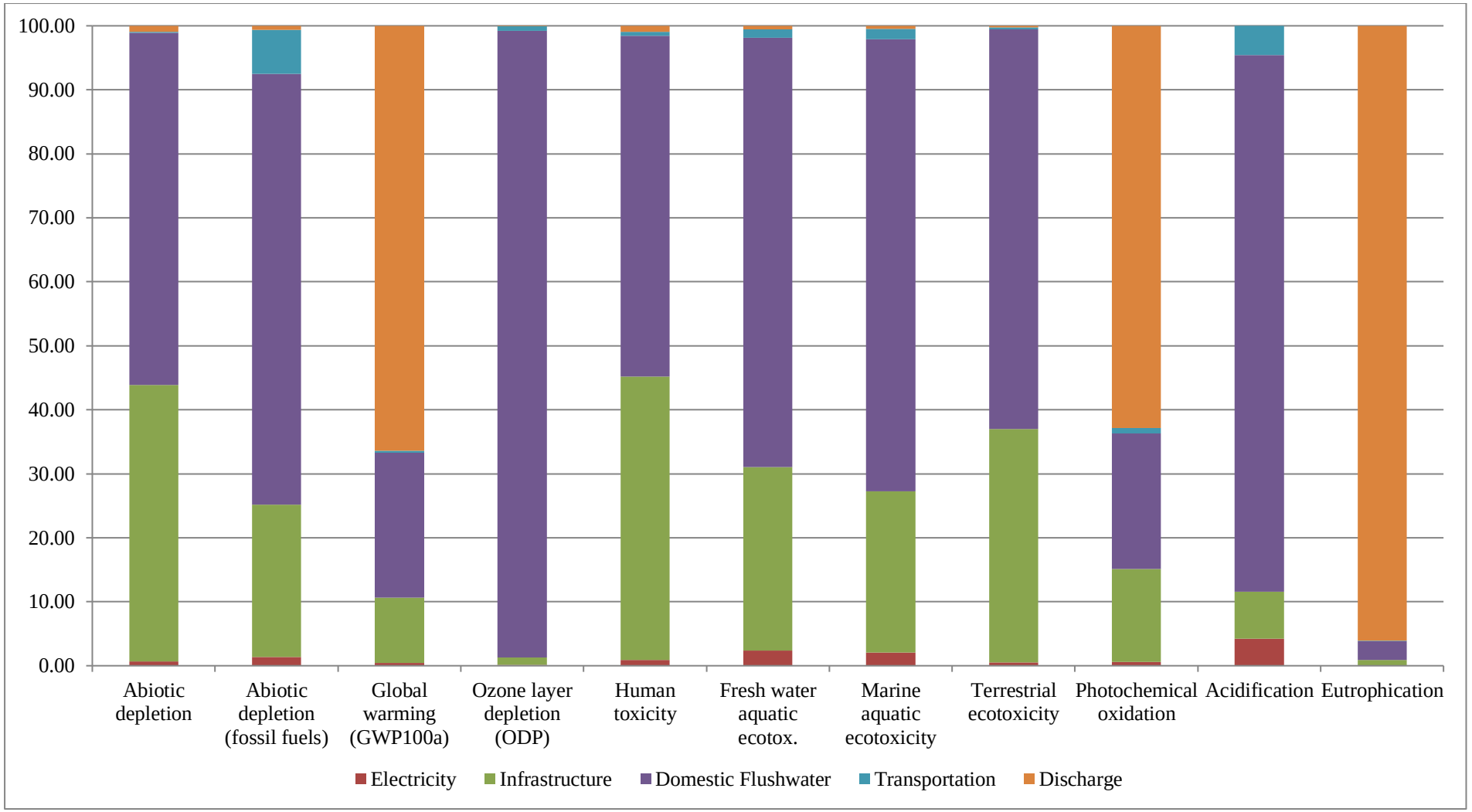

Figure 38: Impact assessment results by main input categories for System A

Figure 39 illustrates the percentage contribution to environmental impacts per process. Evidently it is clear that wastewater conveyance is the largest contributor across most impact categories. Wastewater conveyance, however, is not the main contributor for global warming, Photochemical oxidation and eutrophication. For global warming, the settler (digester) contributes the largest portion (36.57%), followed by the anaerobic baffled reactor (33.72%) and lastly wastewater conveyance (27.88%). Similarly, for photochemical oxidation, the Settler contributes the most with 35.67% followed by the ABR which contributes 33.75%. In the impact Category of eutrophication, irrigation is by a considerable margin the primary contributor (96.14%) to this impact category. The anaerobic baffled reactor contributes a significant portion to most impact categories except for ozone layer depletion and eutrophication. However, the ABR is not the primary contributor for any of the impact categories. Comparatively, the Constructed Wetlands and Sludge Drying Bed have little impact on all impact categories considered. The largest contribution to an impact category for the constructed wetlands is to marine aquatic ecotoxicity with 4.90%.

An observation based on these results is that if the environmental improvement of **System A** is to be optimized the flushwater and wastewater conveyance requires attention in order to reduce the potable water requirements of **System A**. With respect to eutrophication, it has been modelled in SimaPro such that the discharge of nutrients (from the incomplete removal of nutrients in the constructed wetlands) into the environment is a cause of river pollution. The excess nitrogen and phosphorous could potentially be beneficial for plants and irrigated into adjacent fields, however, the worst-case scenario was only considered in **System A**

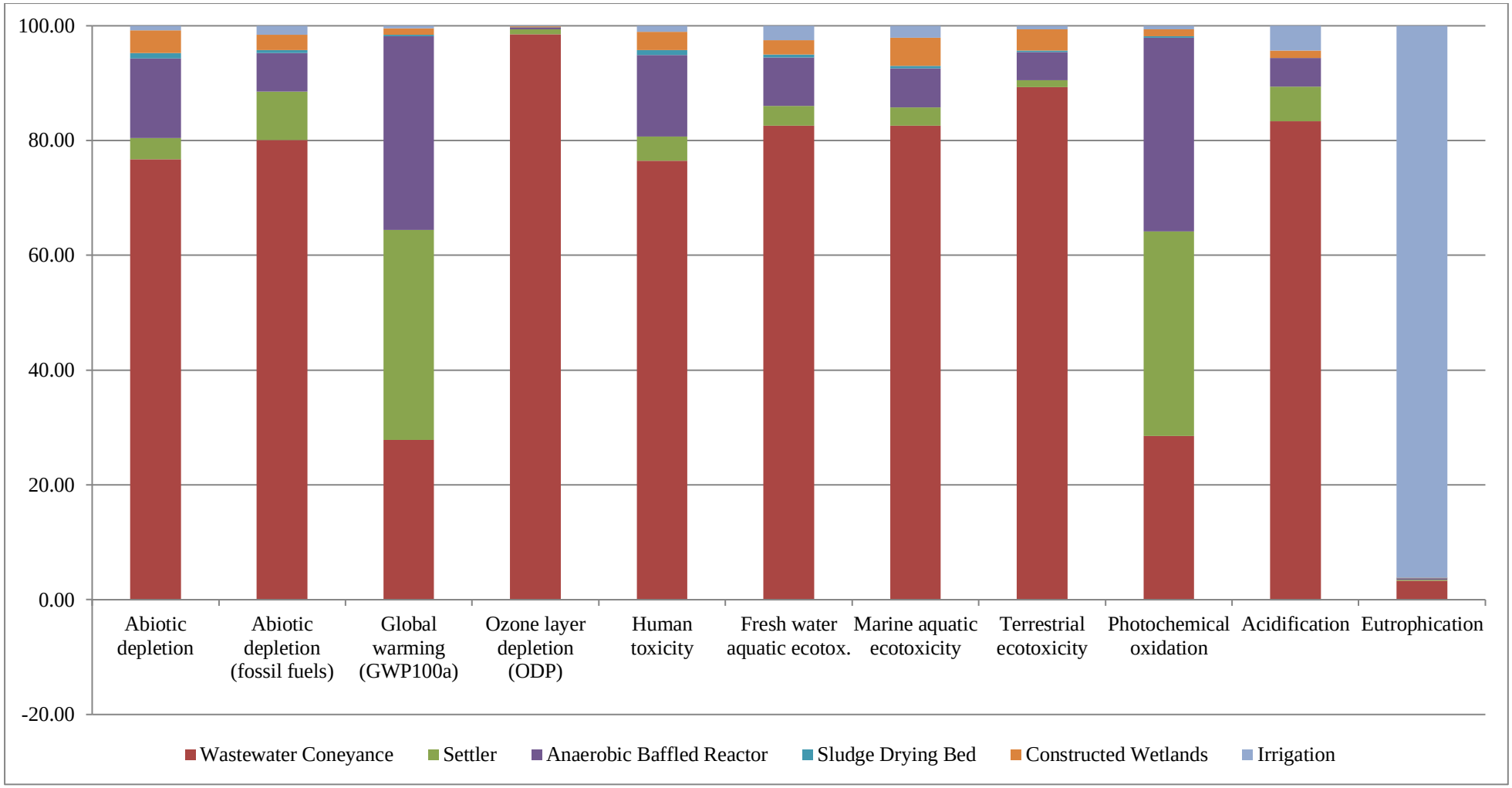

Figure 39: Impact assessment results by process for System A

Shown in **Figure 40** is the impact assessment results by construction and O&M for **System A.** From this diagram, it is apparent that both construction and O&M contribute significantly across all impact categories considered. However, in all impact categories, O&M contributes more significantly than construction. Therefore, improvement of this life stage will have a larger influence on the environmental performance of the system. This improvement is directly linked with the potential for optimizing the use of municipal water. Furthermore, water itself is a scarce resource in the South African context. The impact category in which construction influences most significantly is human toxicity with 44.33% and the impact category which construction influences the least is eutrophication with 0.81%. Conversely, O&M contributes the most significant portion to eutrophication with 99.19% and least significantly to human toxicity with 55.67%.

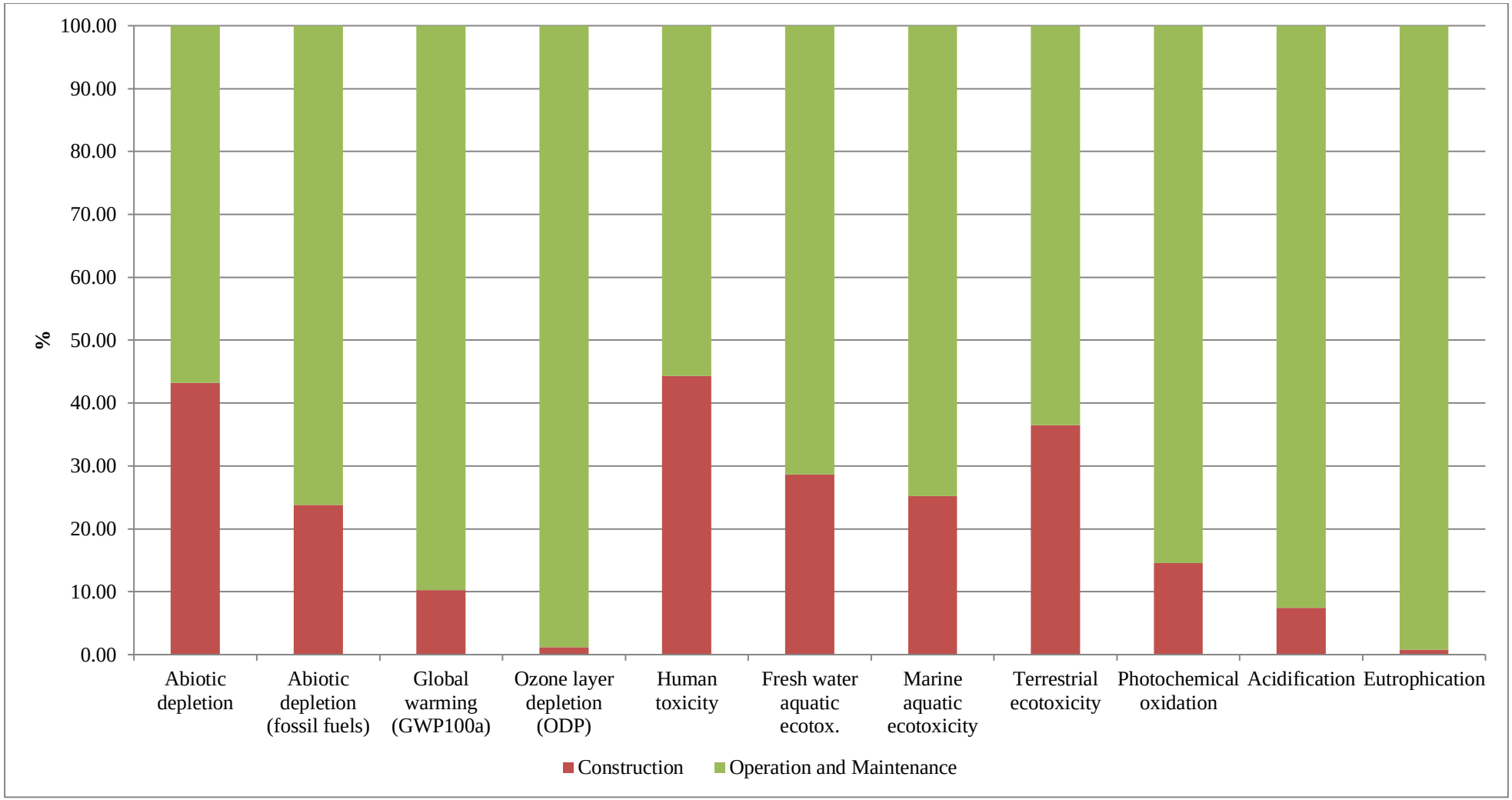

Figure 40: Impact assessment results by O&M and Construction for System

6.2.2. Impact Assessment Results for System B – Use of Low Water Consumption Toilets

The life cycle impact assessment results for **System B** are shown for individual inputs (**Figure 41**), thereafter by main input groups (**Figure 42**), by process (**Figure 43**) and lastly by construction and O&M (**Figure 44**). Similar to **System A**, domestic water consumption accounts for a major portion of most of the environmental impact categories considered. It needs to be noted that **System A** and **System B** differ in the amount of water used for flushing toilets.

Shown in **Figure 41** are the life cycle impact assessment result by material inputs for **System B**. **Figure 41** demonstrates the significance of domestic water consumption across all impact categories considered. The impact category in which domestic water consumption has the lowest influence is human toxicity (47.24%) and the impact category that is most highly influenced by domestic flushwater is ozone layer depletion (97.49%). Although not as significant as domestic flushwater, reinforcing steel and cast iron have a significant influence across many impact categories. Cast iron accounts for a significant portion of terrestrial ecotoxicity (37.64%), human toxicity (22.64%), abiotic depletion (20.58%), fresh water aquatic ecotoxicity (16.75%), photochemical oxidation (16.48%), global warming (12.64%), marine aquatic ecotoxicity (12.5%), eutrophication (8.06%) and abiotic depletion (7.94%). Similar to the environmental impacts seen for cast iron, reinforcing steel significantly impacts most impact categories except for Ozone layer depletion. Reinforcing steel contributes a notable portion of the environmental impacts to human toxicity (25.19%) and abiotic depletion (25.06%). Moreover, it is important to also notice the positive influence of reinforcing steel and cast iron on acidification. As previously mentioned in **Section 6.2.1**, in the production of cast iron and steel, two avoided products including cement clinker and natural gas account for this positive contribution. Several input materials result in significant impacts in only a few of the considered impact categories. Concrete significantly impacts only two impact categories, namely global warming (6.43%) and acidification (5.4%). Diesel accounts for 8.56% of the impacts to abiotic depletion (fossil fuels) and 5.69% to acidification. Brick accounts for 4.9% of the impacts to marine aquatic ecotoxicity, electricity accounts for 5.15% of impacts to acidification and PVC-U accounts for 5.27% of

Abiotic depletion (fossil fuels). The environmental impacts associated with the input of LLDPE and HDPE are negligible.

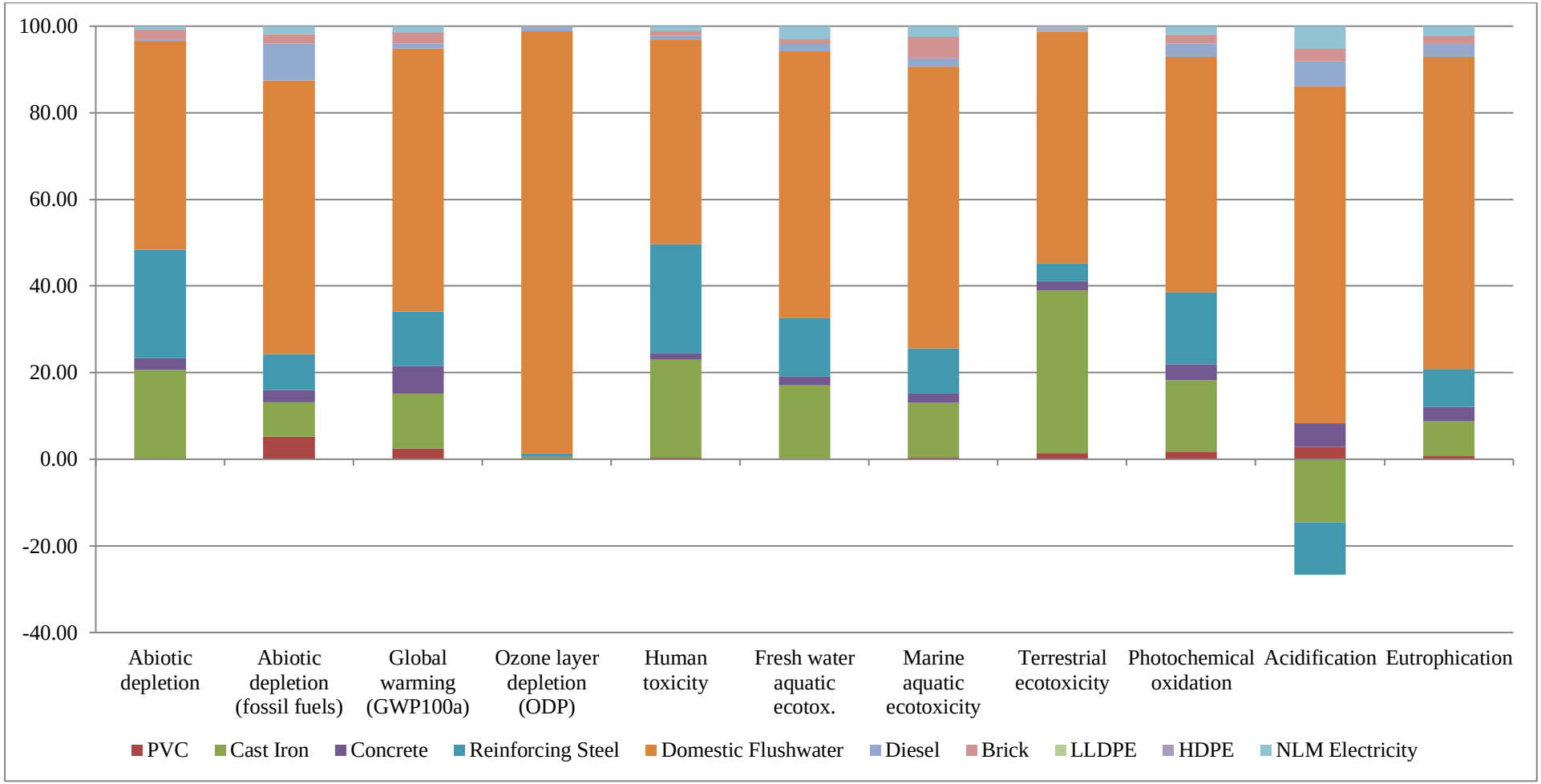

Figure 41: Impact assessment results for all system inputs for System B

Figure 42 shows the environmental impacts assessment results by main input category for **System B**. Again, this diagram demonstrates the large influence of domestic water consumption many impact categories. Domestic flushwater is the primary contributor for abiotic depletion fossil fuels (62.98%), Ozone layer depletion (97.48%), freshwater aquatic ecotoxicity (61.59%), marine aquatic ecotoxicity (65.04%), terrestrial ecotoxicity (53.47%) and acidificiation (87.74%). Discharge to the environment is the primary contributor in three impact categories namely global warming (58%), photochemical oxidation (55%) and eutrophication (92%). Infrastructure contributes significantly to a spread of impact categories but is only the primary contributor to abiotic depletion (50.77%) and human toxicity (50.88%). For the impact category of acidification, infrastructure has a positive influence. The positive influence on acidification stems from the avoided products of cement clinker and natural gas in the production of cast iron and reinforcing steel. Transportation significantly contributes to two of the impact categories considered, namely abiotic depletion (fossil fuels) with 8.49% and acidification with 6.36%. The least influential input group is electricity. Electricity significantly influences only acidification significantly with 5.80% for this impact category.

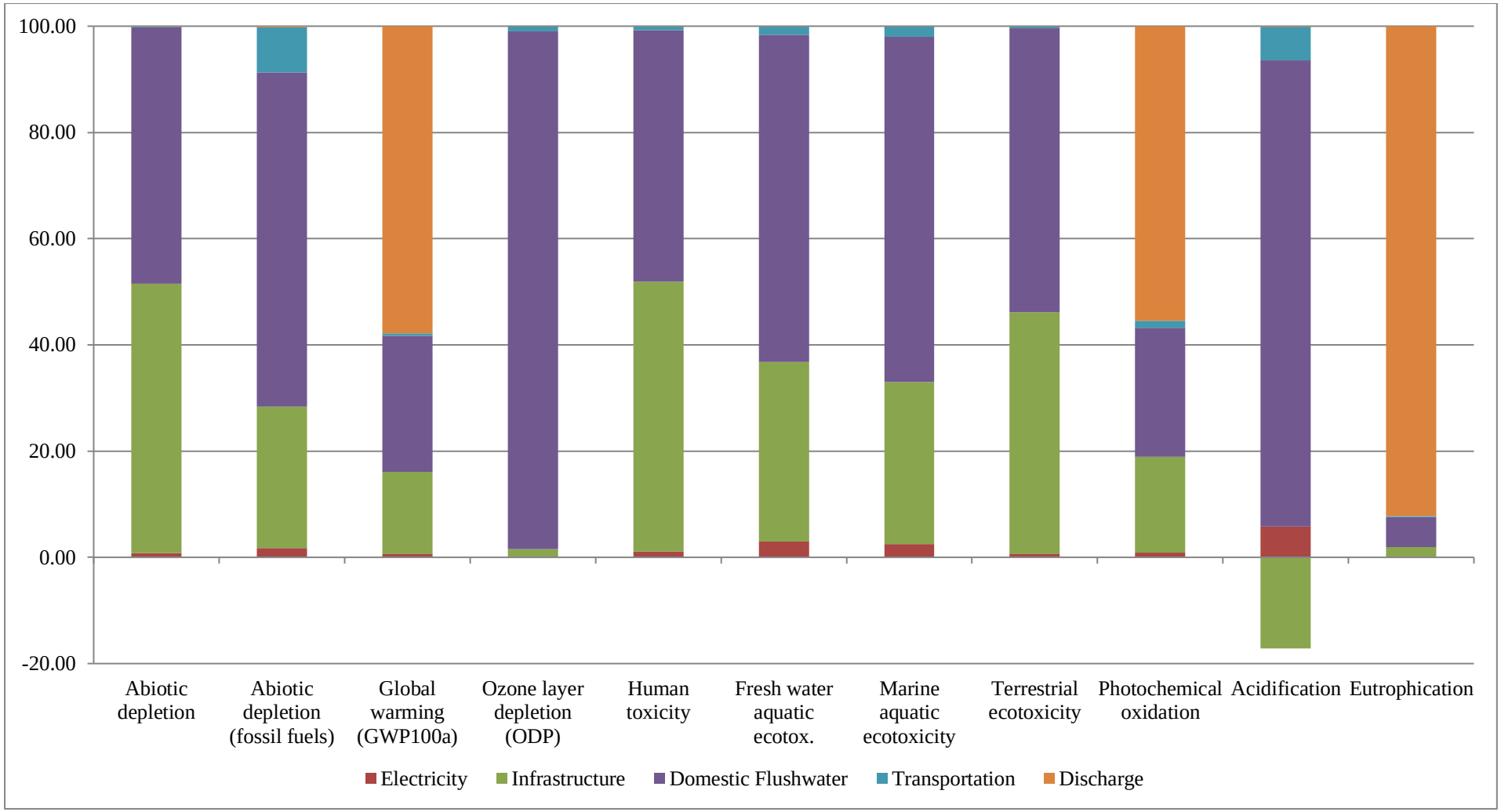

Figure 42:Impact assessment results by main input categories for System B

Figure 43 is a diagram representing the impact assessment results by process for **System B**. Wastewater conveyance dominates the contribution to environmental impacts across all impact categories except for three. The impact category that wastewater conveyance contributes the least percentage is eutrophication (6.46%) and the impact category that wastewater conveyance contributes the highest percentage is ozone layer depletion (98.15%). The anaerobic baffled reactor contributes significantly to all impact categories except for ozone layer depletion and eutrophication. The positive contribution of the ABR unit is due to the avoided products cement clinker and natural gas in the production of cast iron and steel. The settler is a primary contributor to global warming (41.98%) and photochemical oxidation (41.38%). Moreover, the settler contributes significantly to all impact categories excluding ozone layer depletion and eutrophication. The constructed wetlands contribute relatively less than the aforementioned processes. The highest portion of environmental impacts that the constructed wetlands is responsible for is 5.99% for the marine aquatic ecotoxicity impact category. Irrigation is the primary contributor to eutrophication (92.39%) and does not significantly impact any other impact category. The environmental impacts of the sludge drying bed are considered to be negligible.

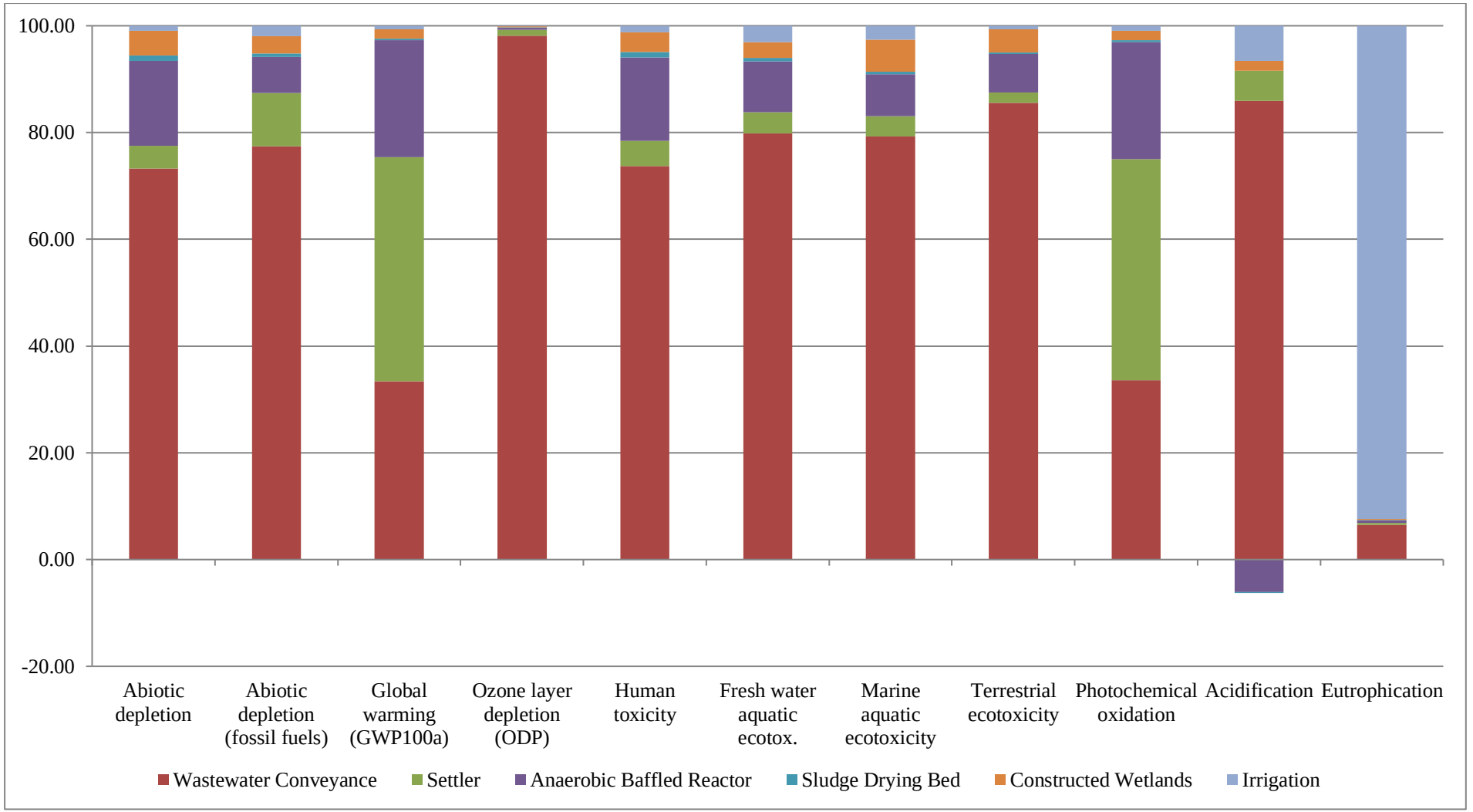

Figure 43:Impact assessment results by process for System B

Shown in **Figure 44** is the impact assessment results for construction and O&M for **System B**. This analysis showed a similar spread of results as seen in the construction and O&M results in **System A**. Both construction and O&M are significant across all impact categories considered. However, overall operation and maintenance is the primary contributor for nine out of the eleven impact categories including abiotic depletion fossil fuels (73.39%), global warming (84.49%), ozone layer depletion (98.57%), freshwater aquatic ecotoxicity (66.18%), marine aquatic ecotoxicity (69.53%), terrestrial ecotoxicity (54.45%), photochemical oxidation (81.93%), acidification (100%) and eutrophication (98.23%).

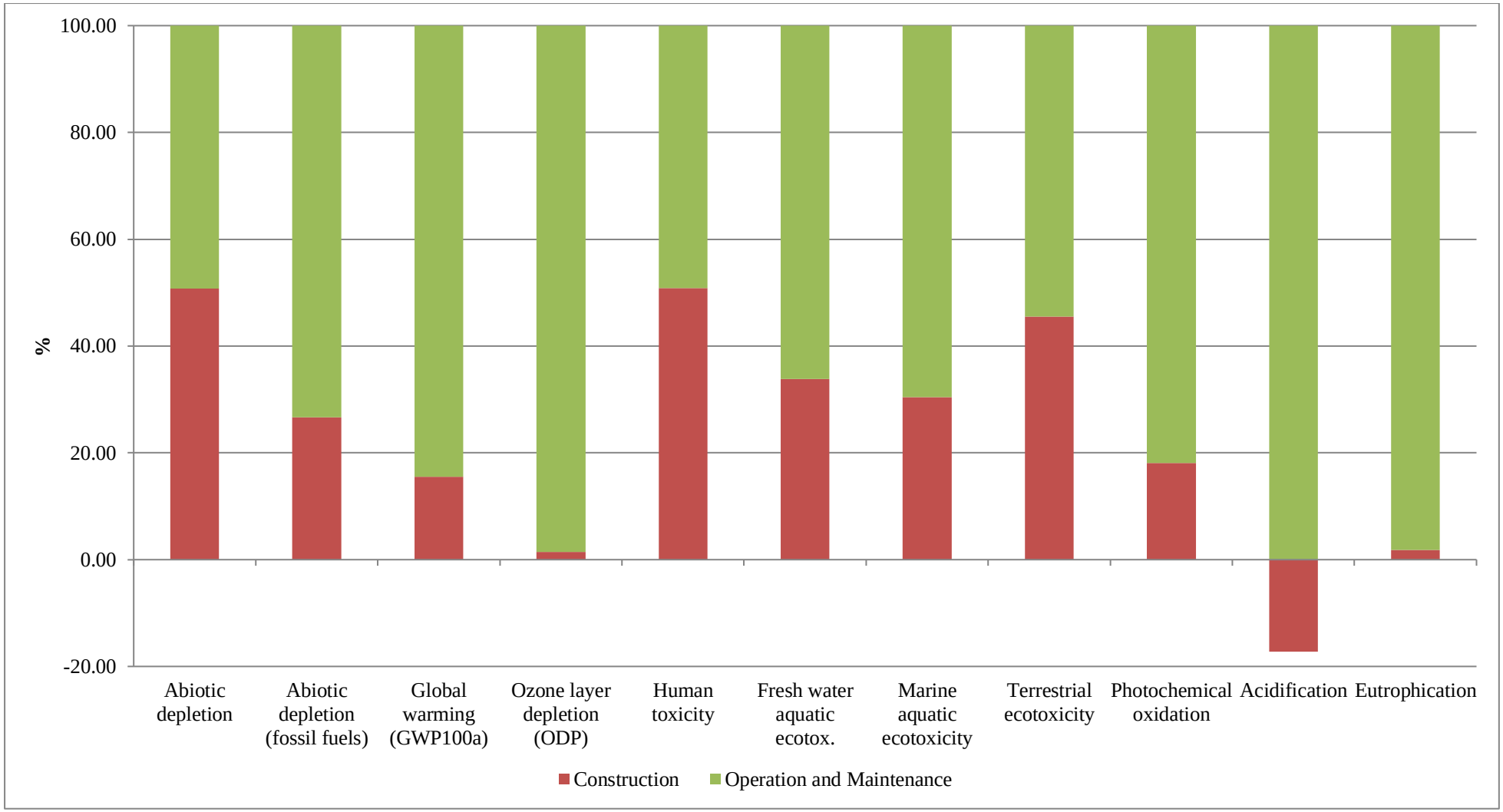

Figure 44: Impact assessment results by O&M and Construction for System B.

6.2.3. Impact Assessment Results for System C

The life cycle impact assessment results for **System C** are shown for individual inputs (**Figure 45),** thereafter by main input groups (**Figure 46**), by process (**Figure 47**) and lastly by construction and O&M (**Figure 48**). It needs to be mentioned that **System C** differs from **System A** and **B** since **System C** does not consider the influence of wastewater conveyance and domestic water consumption. The purpose of analysing **System C** is to observe in greater detail the significant environmental impacts of the DEWATS in isolation.

Figure 45 shows the environmental impacts of **System C** by individual inputs. The input material that contributes most significantly across many impact categories is reinforcing steel. Reinforcing steel is the primary contributor to abiotic depletion (63.15%), global warming (40.73%), human toxicity (64.53%), fresh water aquatic ecotoxicity (45.39%), marine aquatic ecotoxicity (33.69%), photochemical oxidation (45.43%) and eutrophication (34.97%). Interestingly, reinforcing steel also contributes in a positive manner to the environmental impact category of acidification (-47%). This positive contribution is attributed to the avoidance of cement clinker and natural gas in the production of cast iron and steel. Similar to reinforcing steel, cast iron accounts for a significant portion of the environmental impacts across most impact categories. Cast iron is the major contributor for terrestrial ecotoxicity, accounting for 61.30% of the impact to that category. Similar to reinforcing steel, cast iron also contributes positively (-19%) to acidification. The positive contribution is also attributed to the avoidance of cement clinker and natural gas. Diesel fuel contributes largely across a number of impact categories. Diesel is the most significant contributor to three impact categories namely abiotic depletion (fossil fuels) accounting for 38.62%, ozone layer depletion (52.91%) and lastly acidification (32.93%). Diesel also contributes a significant, but not major, portion to global warming (5.7%), human toxicity (3.09%), fresh water aquatic ecotoxicity (8.35%), marine aquatic ecotoxicity (9.79%), photochemical oxidation (12.68%) and eutrophication (18.02%). Brick accounts for a significant portion of environmental impacts across all impact categories excluding terrestrial ecotoxicity. The impact category in which brick has the most influence is acidification (16.74%). Similar to

brick, electricity contributes significantly across all impact categories excluding one category – abiotic depletion. For the impact category of acidification, electricity accounts for a major portion (29.42%). The thermoplastics (PVC-U, HDPE and LLDPE) used for the construction of the DEWATS plant contribute an insignificant portion across all impact categories

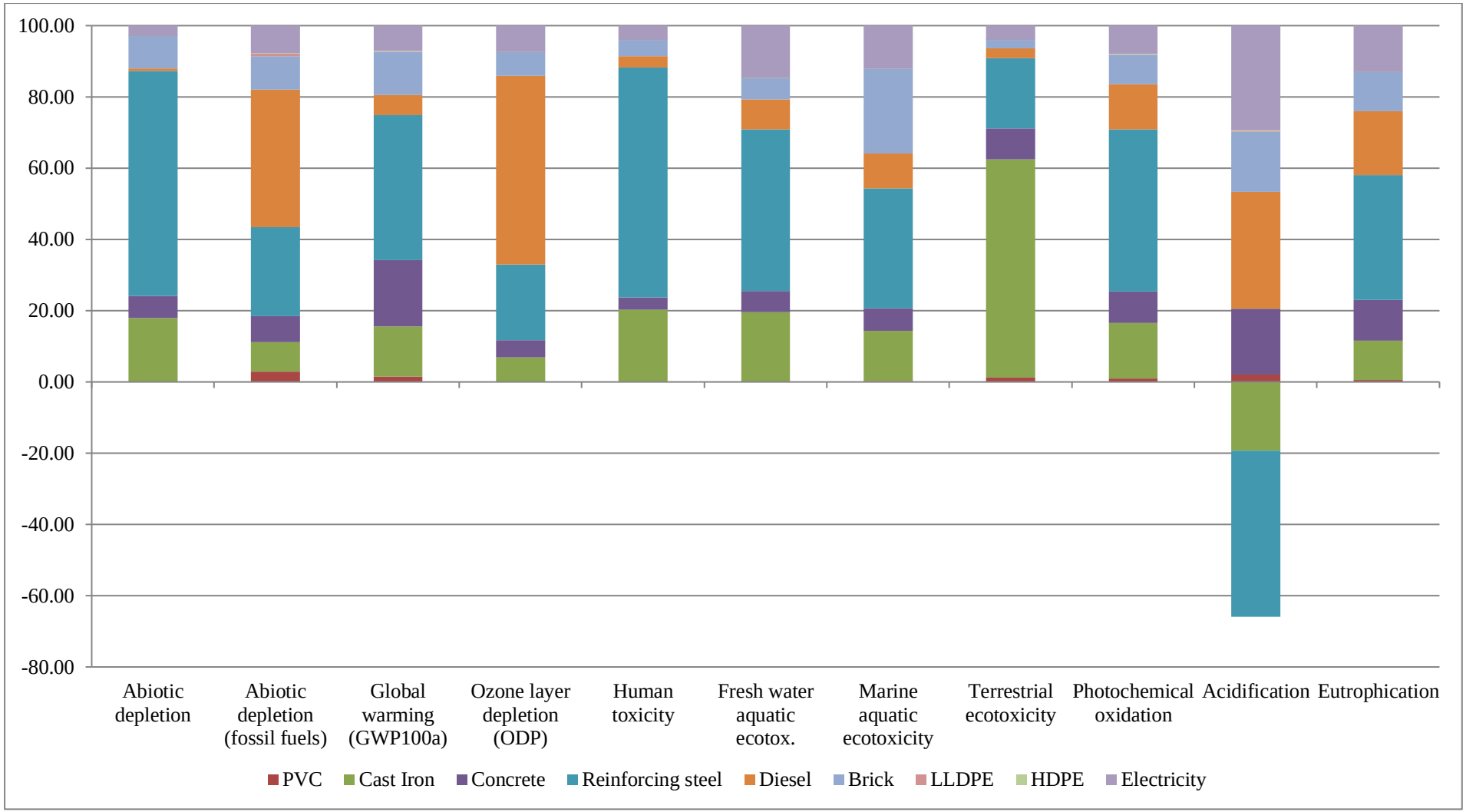

Figure 45: Impact assessment results for all system inputs for System C

Figure 46 shows the environmental impacts of **System C** by main input categories. The main input categories considered includes infrastructure, electricity and transportation. Domestic water consumption was excluded from **System C** since the process of wastewater conveyance was excluded.

The diagram overleaf demonstrates the major contribution of infrastructure across most impact categories. Infrastructure is the major contributor to abiotic depletion (96.39%), abiotic depletion fossil fuels (52.88%), global warming (86.98%), human toxicity (92.93%), fresh water aquatic ecotoxicity (77.05%), marine aquatic ecotoxicity (78.13%), terrestrial ecotoxicity (93.12%), photochemical oxidation (79.20%), and eutrophication (68.93%). Transportation contributes significantly across all impact categories excluding abiotic depletion and terrestrial ecotoxicity. Transportation is the primary contributor to two impact categories including ozone layer depletion (52.91%) and acidification (52.47%). Electricity contributes significantly across all impact categories except for abiotic depletion. Electricity is not a primary contributor for any of the impact categories, however, electricity does contribute a large portion to acidification (46.88%).

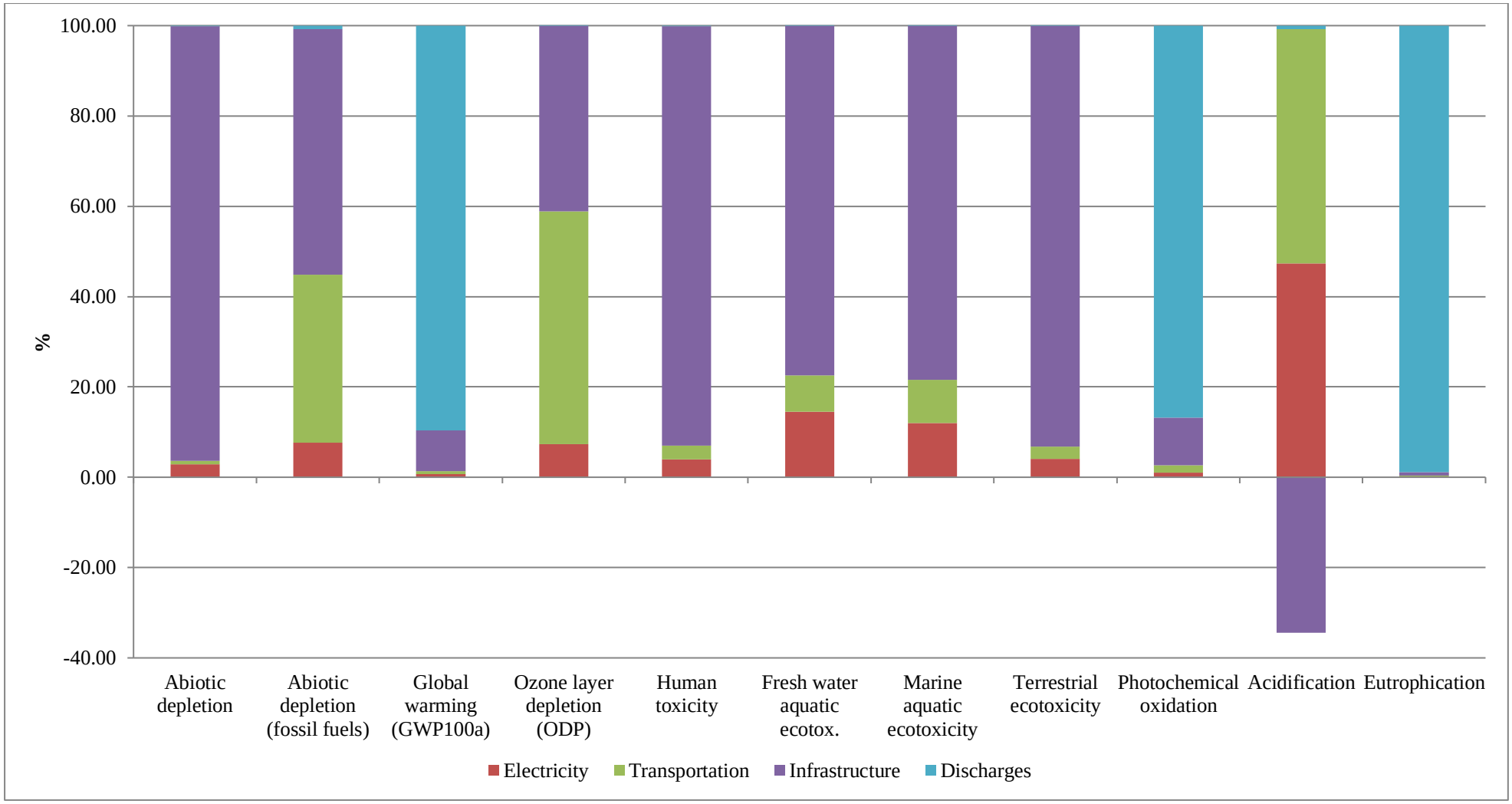

Figure 46: Impact assessment results by main input categories for System C

Figure 47 shows the environmental impacts by process for **System C**. The diagram clearly shows the dominant major contribution of the anaerobic baffled reactor across most impact categories. The ABR is the primary contributor to abiotic depletion (59.40%), global warming (51.09%), human toxicity (59.08%), fresh water aquatic ecotoxicity (46.81%), marine aquatic ecotoxicity (37.54%), terrestrial ecotoxicity (50.91%), photochemical oxidation (47.01%) and eutrophication (39.53%). Importantly, the diagram also demonstrates the positive contribution of the ABR to acidification. The positive contribution of the ABR to acidification is attributed to the avoided products of cement clinker and natural gas in the production of steel and cast iron. The settling unit also contributes significantly across all impact categories. The settling unit is the major contributor to two impact categories including abiotic depletion fossil fuels (44.09%) and ozone layer depletion (57.17%). The constructed wetlands also contribute significantly across all impact categories, however, it is not the primary contributor for any impact category. The process of irrigation contributes significantly across all impact categories. Irrigation is the primary contributor to acidification accounting for 44.03% of the impacts to this category. The sludge drying is the least environmentally burdensome processing unit. The process of sludge drying contributes an insignificant portion to ozone layer depletion, marine aquatic ecotoxicity and terrestrial ecotoxicity.

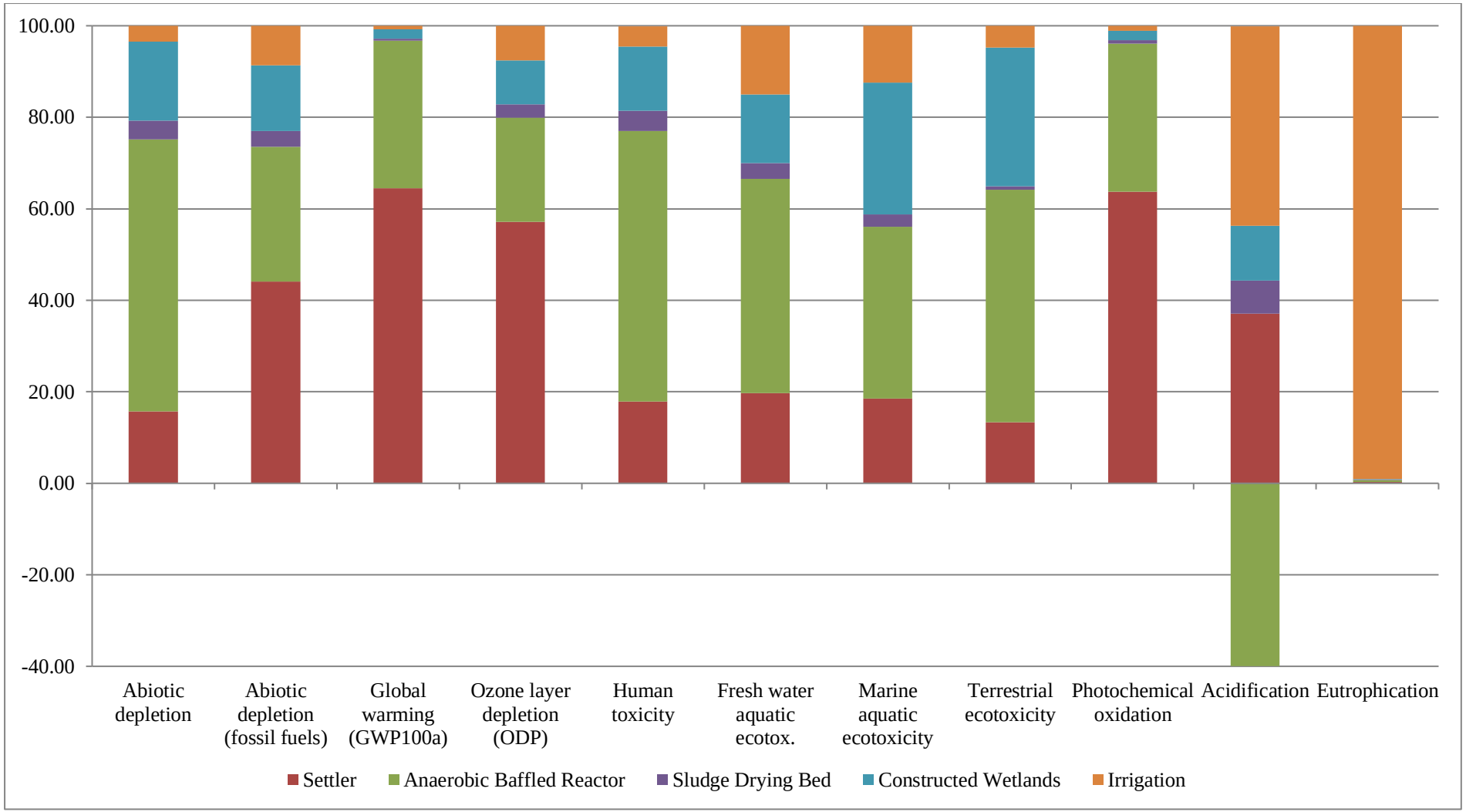

Figure 47: Impact assessment results by process for System C

The impact assessment result for construction and O&M is shown in **Figure 48**. In this particular system, the contribution of the sewer network as well as domestic flushwater was omitted. The results of the SimaPro model for this scenario indicate that both construction and O&M contribute significantly to most impact categories. O&M, however, contributes the most significant portion to only two impact categories, namely ozone layer depletion (60.25%) and acidification (100%). Conversely, construction contributes less significantly to ozone layer depletion (39.75%) and contributes positively to acidification. The positive contribution to acidification is traced back to the avoidance of products cement clinker and natural gas in the production of cast iron and steel.

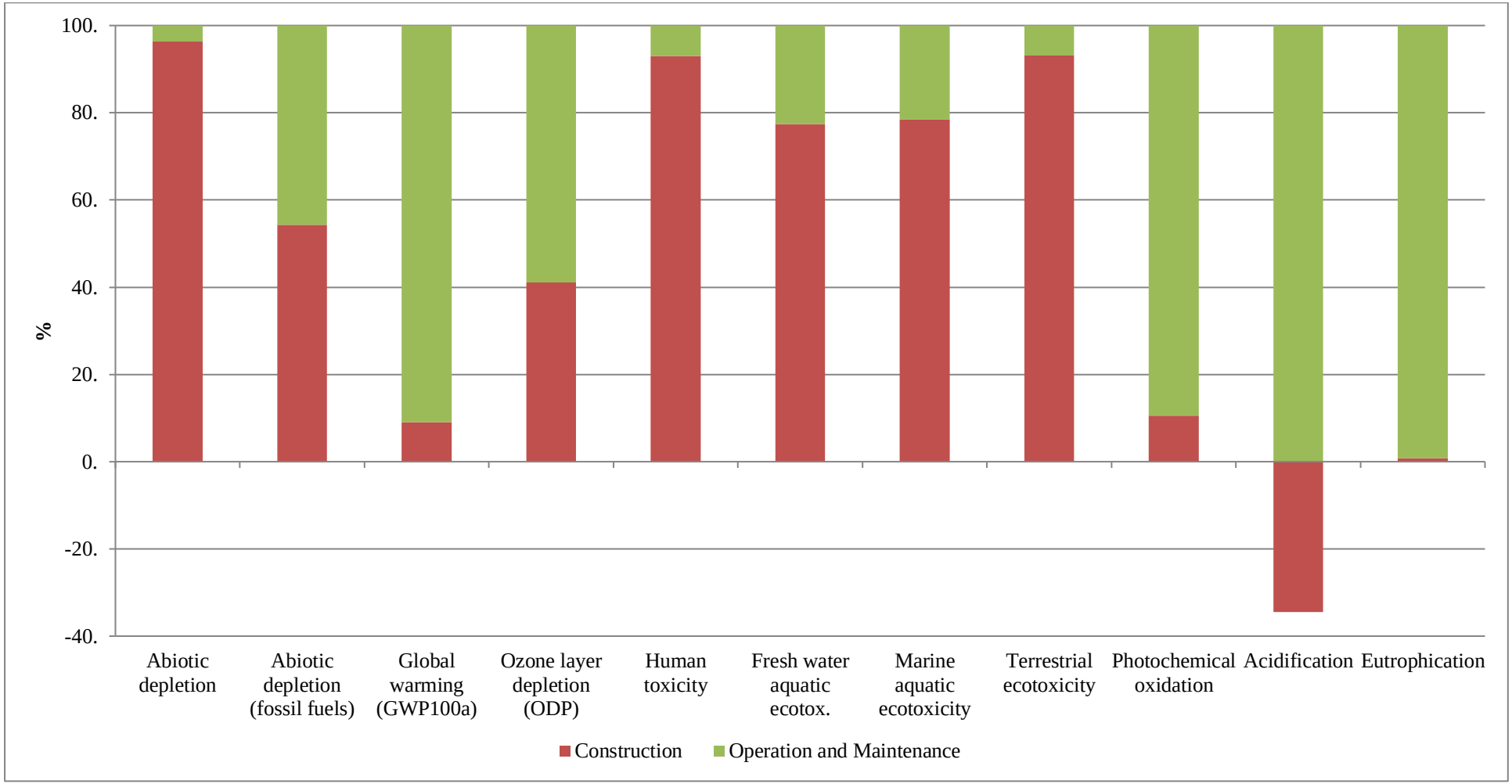

Figure 48: Impact assessment results by O&M and Construction for System C

6.3. Selected Normalised Results

The following section presents normalised results for selected scenarios. **System A** is presented by process and by construction and O&M and **System C** is presented by process and by construction and O&M. The purpose of presenting normalised results is to highlight the predominant areas of concern with regard to the environmental profile of the systems investigated. The normalisation step was undertaken using global reference values from the year 1995 and can be seen in **Appendix J**.

6.3.1. System A

Shown overleaf in **Figure 49** is the normalised impact assessment results for **System A** demonstrating the significant processes and environmental impact categories. The most significant impact category for the NLM DEWATS (including the sewer network and wastewater conveyance) is marine aquatic ecotoxicity. The process that contributes most significantly to this impact category is wastewater conveyance. More specifically, the electricity required in the water treatment process. South Africa's electricity is predominantly produced from thermal power generated from the burning of coal. The large spike in marine aquatic ecotoxicity shown in **Figure 49** is mainly due to heavy metals emitted to water bodies from the disposal of coal mining spoil.

The second most significant impact category as shown in **Figure 49** is eutrophication. The irrigation process is shown to be the most significant contributor to eutrophication. To a lesser extent, freshwater aquatic ecotoxicity, global warming and abiotic depletion (fossil fuels) are shown to be significant in the overall environmental profile of **System A**. For the impact category of freshwater aquatic ecotoxicity, wastewater conveyance is significant. For global warming, the share of impacts is distributed evenly between wastewater conveyance, the settling unit and the anaerobic baffled reactor. Lastly, for abiotic depletion (fossil fuels) wastewater conveyance is the primary contributor.

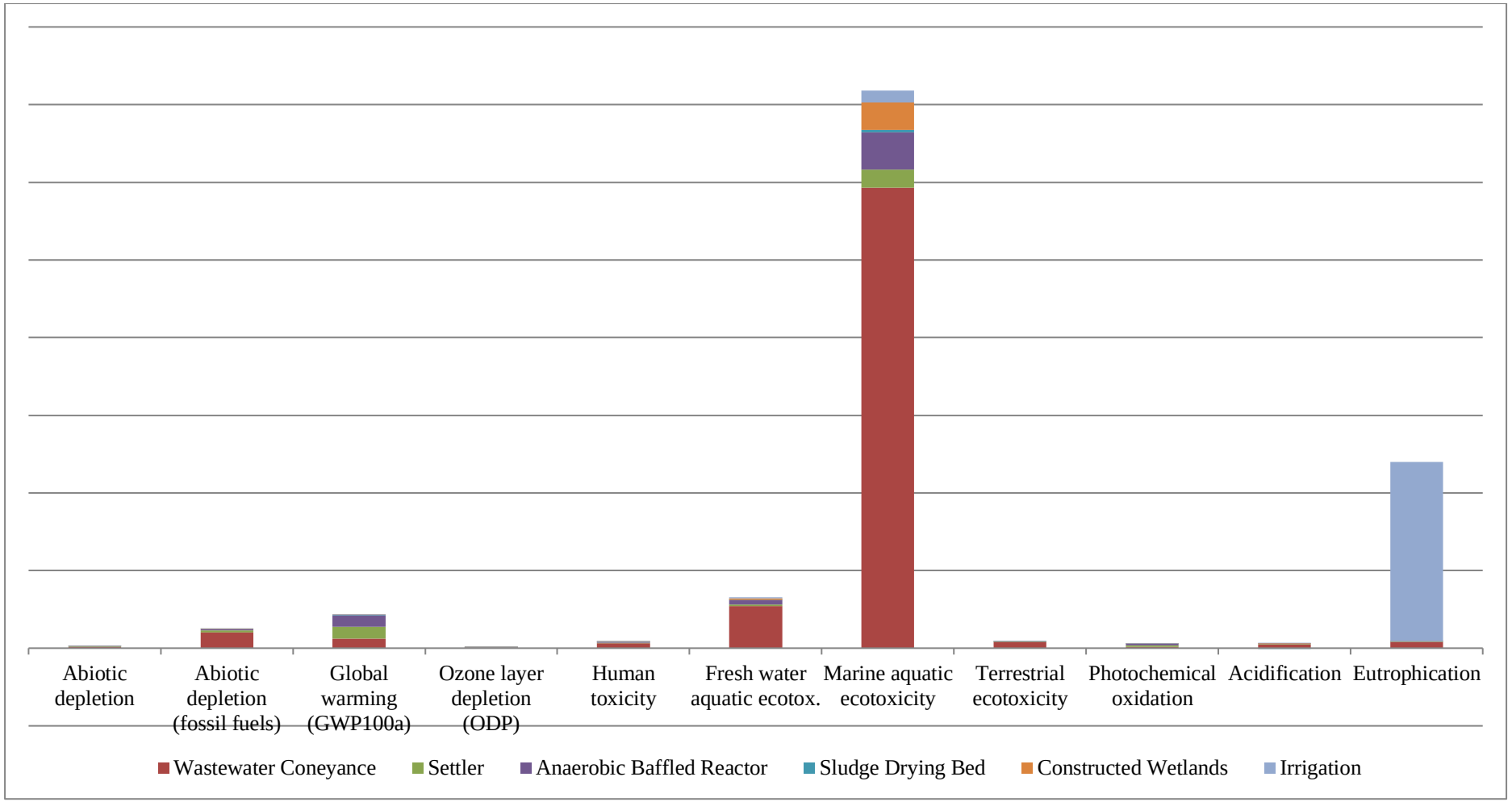

Figure 49: Normalised impact assessment results by process for System A

Seen in **Figure 50** is the normalised impact assessment results for **System A** for construction and O&M. As discussed previously, the environmental profile shows that marine aquatic ecotoxicity is the most significant impact category. For marine aquatic ecotoxicity O&M contributes 75% of the environmental impacts to this impact category whilst construction contributes 25%. The contribution of O&M to this category stems from the disposal of fly ash at dry dumps in the supply chain of energy used to power the water supply treatment works. The second most significant impact category is eutrophication. For eutrophication, the primary contributor is O&M which is linked to the irrigation and runoff of nutrients into fresh water bodies. freshwater aquatic ecotoxicity, global warming and abiotic depletion (fossil fuels) also contribute a lesser yet significant portion to the overall environmental profile. For all of the aforementioned impact categories, O&M is the primary contributor.

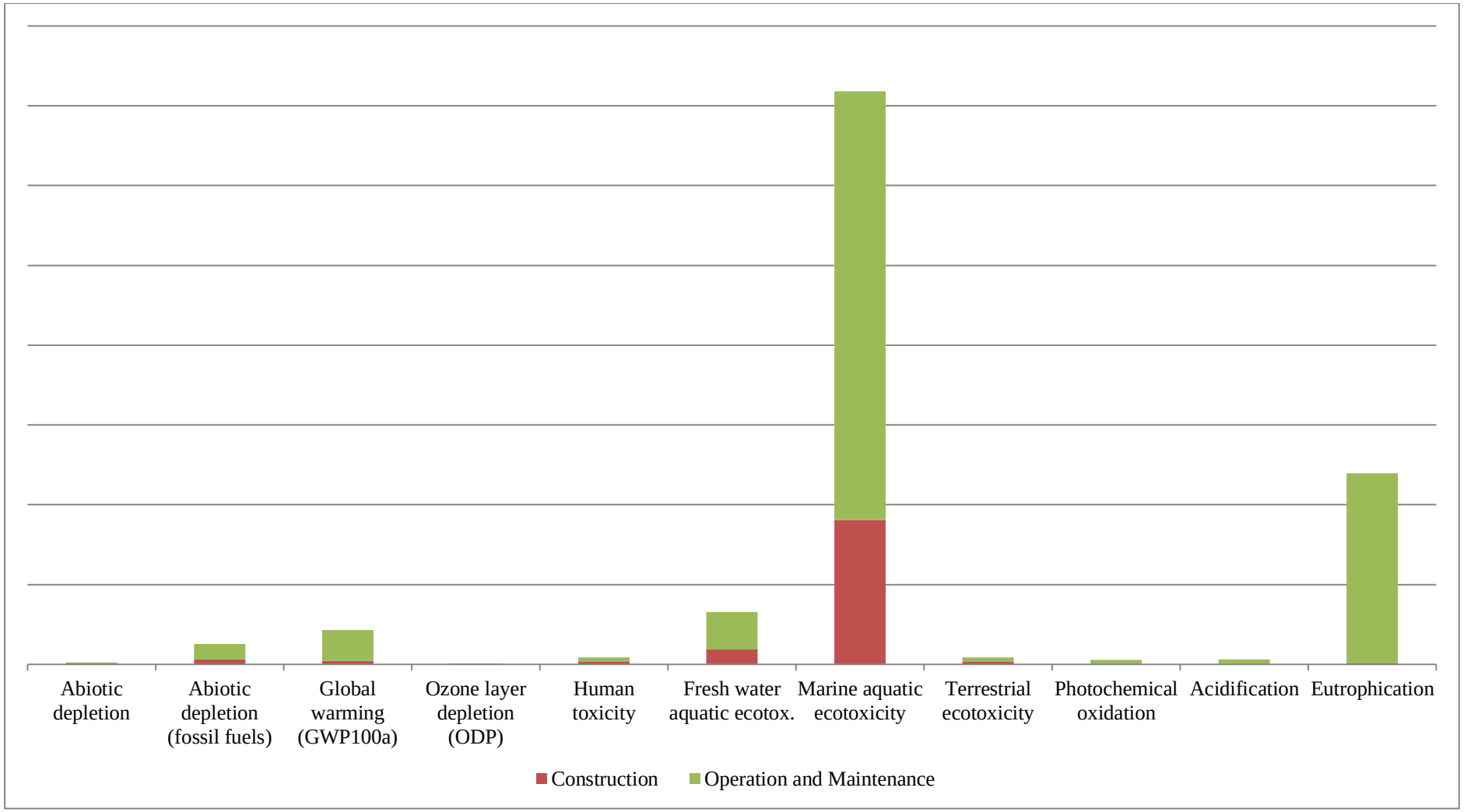

Figure 50: Normalised impact assessment results by construction and O&M for System A

6.3.2. System C

Figure 51 shows the normalised impact assessment results for **System C** demonstrating the significant impact categories and processes involved. As described in **Section 5.5** of this dissertation, **System C** includes the NLM DEWATS, however, it excludes the existing sewer network and wastewater conveyance process. The environmental profile for this particular scenario demonstrates the significance of marine aquatic ecotoxicity and eutrophication. The primary contributors to the impact category of marine aquatic ecotoxicity is the ABR and more specifically the use of cast iron covers and large amounts of reinforcing steel in the structure. The production of cast iron and steel is highly energy intensive. Marine aquatic ecotoxicity stems from the emission of heavy metals during the disposal of coal mining spoil. The overwhelming contributor to eutrophication is irrigation due to the incomplete removal of nutrients in the constructed wetlands. The third most significant impact category in the environmental profile shown overleaf is global warming. The main contributor to global warming is the settler followed by the ABR. In the settling unit and ABR, methane is released under anaerobic conditions and can be attributed directly to global warming. The last significant impact category worth discussing is freshwater aquatic ecotoxicity. For freshwater aquatic ecotoxicity, the primary contributor is the reinforcing steel and cast iron required for the ABR unit. As mentioned earlier, the heavy metals emitted fly ash at dry dumps and irrigated ash dump sites is the cause of marine and freshwater aquatic ecotoxicity.

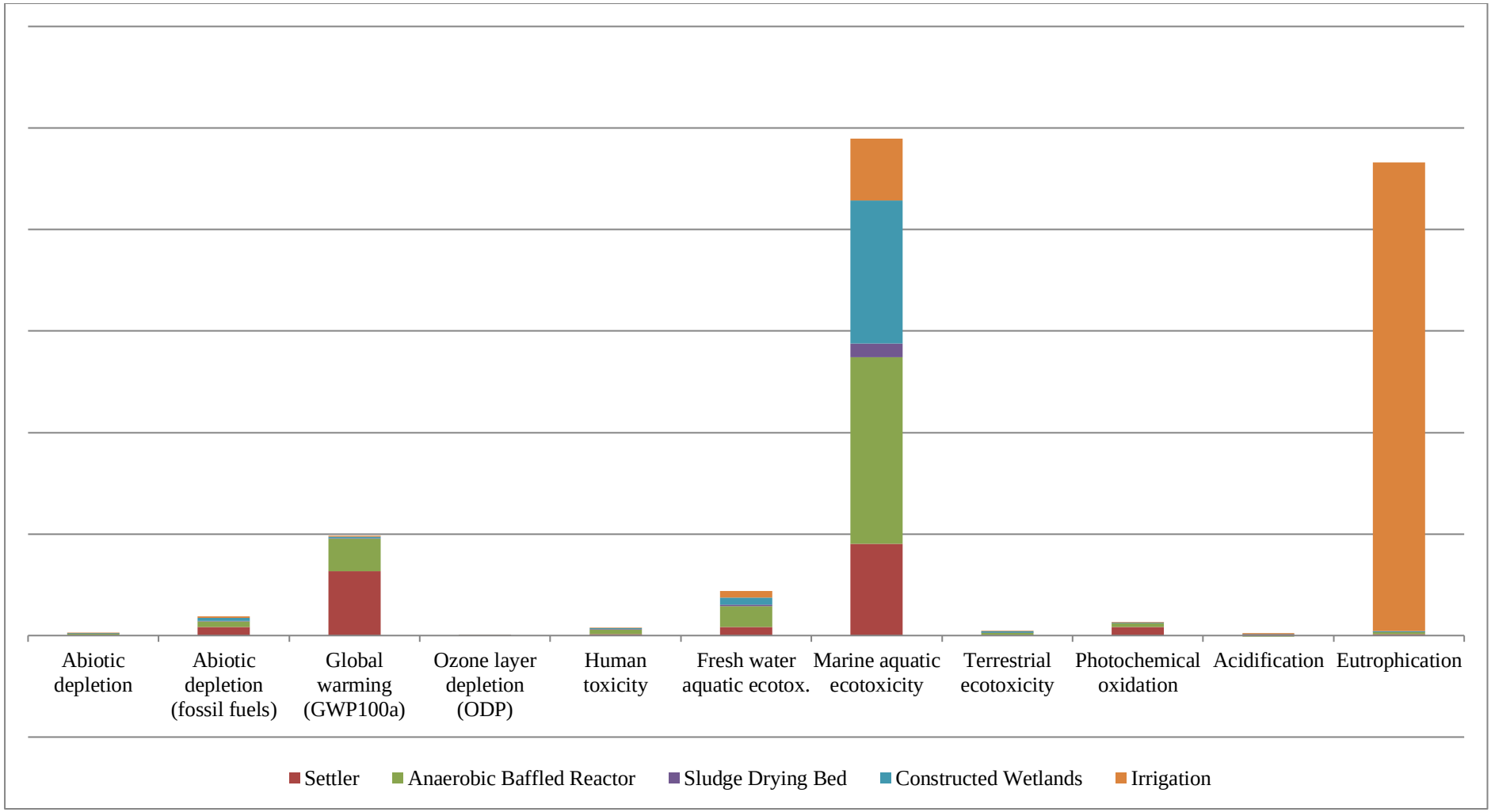

Figure 51: Normalised impact assessment results by process for System C

Shown in **Figure 52** is the normalised impact assessment results for **System C** by construction and O&M. The environmental profile shows that marine aquatic ecotoxicity is the most significant impact category. The main contributor to marine aquatic ecotoxicity in this scenario is the construction phase. More specifically, this can be attributed to a process involved in the production of cast iron and steel. Since the production of cast iron and steel requires large amounts of electricity, marine aquatic ecotoxicity stems from the emission of heavy metals from the disposal of coal mining spoils. In contrast to the results shown in **Section 6.3.1**, the main contributor to this impact category is construction whereas O&M is the main contributor in **System A**. This demonstrates that regardless of whether domestic water supply is included in the **System B**oundaries, marine aquatic ecotoxicity is the most significant impact category for the normalised results. The second most important impact category considered is eutrophication which is dominated by O&M. More specifically, the incomplete removal of nutrients in the wastewater treatment **System A**nd eventual irrigation is responsible for eutrophication show. The third most significant impact category in the environmental profile is global warming. O&M is the primary contributor to global warming as shown in **Figure 52**, the release of methane gas in the settling unit and ABR contribute largely to this impact category. Lastly, and least significantly, construction contributes largely to freshwater aquatic ecotoxicity which is also related to the emission of heavy metals in the disposal of coal mining waste in the production of electricity used for manufacturing steel and cast iron.

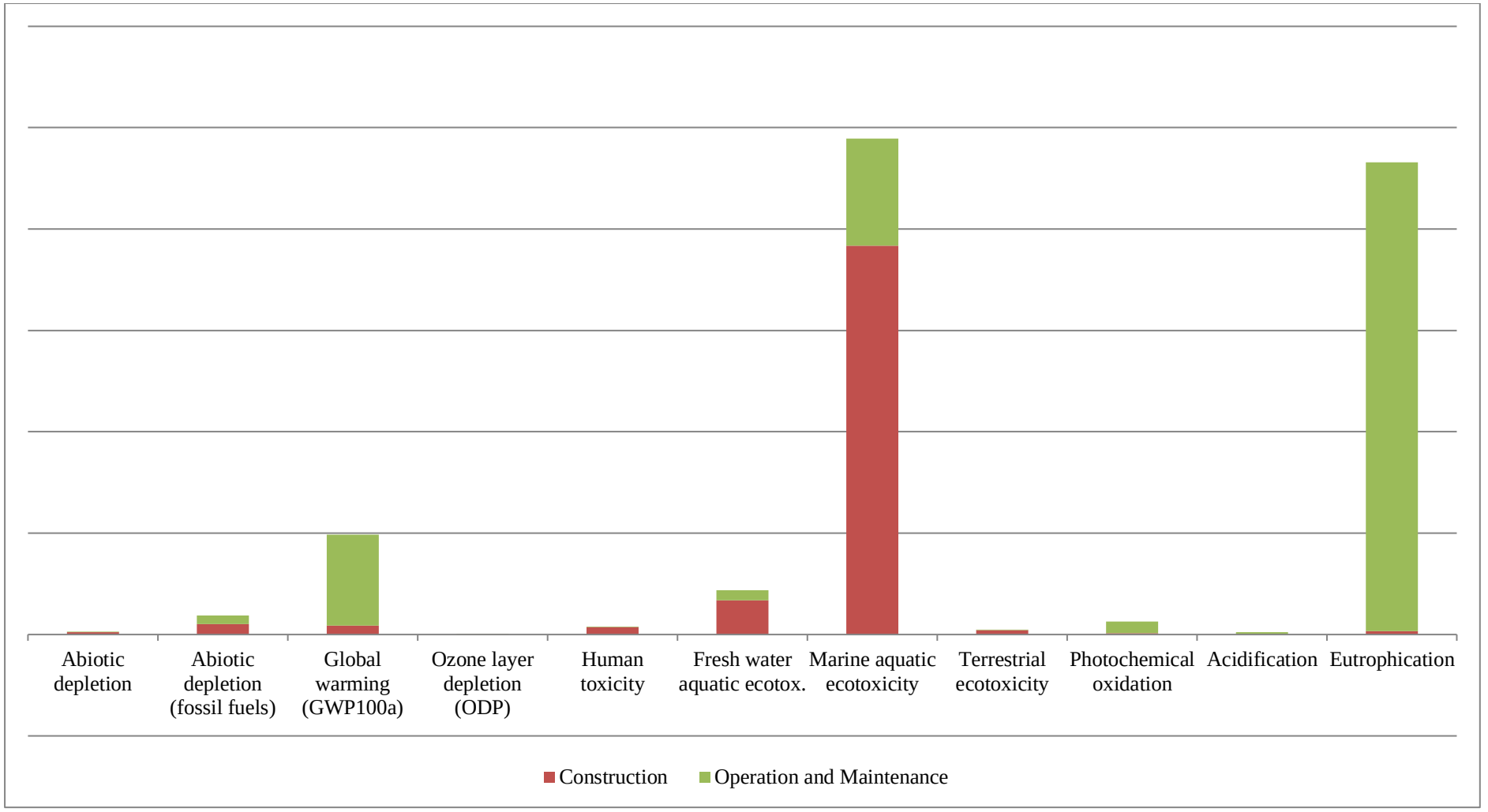

Figure 52: Normalised impact assessment results by construction and O&M for System C

6.4. Summary of LCIA Results

The previous sections presented the results of the LCIA produced by SimaPro software. The results were analysed showing the overall environmental scores, thereafter relative percentage contributions where presented by individual material inputs, by grouped inputs, by process and by construction and O&M. Finally, the normalised impact assessment results for **System A** and **System C** by process and by construction and O&M were presented. In **System A** and **System B**, which both include the sewer network and domestic flushwater for operation, it appears that a significant portion of the overall environmental impacts can be attributed to domestic flushwater. For **System C**, which looks at the DEWATS plant in isolation without the network and domestic water consumption, it appears that infrastructure and in particular reinforcing steel and cast iron contribute significantly to the overall environmental impacts.

Regarding the LCIA results modelled based on construction and O&M, it appears for **System A** and **System B** (including the sewer network and domestic flushwater), that O&M accounted for the most significant portion of environmental impacts. The dominance of O&M for the aforementioned systems is attributed to domestic flushwater. More specifically, the electricity required for the treatment of raw water to municipal standards is responsible for a large portion of the environmental impacts. When comparing **System A** and **System B**, however the environmental impacts due to O&M for **System B** are slightly less overall than **System A**. In **System B**, low flush toilets are implemented which reduce overall domestic water consumption. This reduction in domestic water consumption appears to be the reason why O&M accounts for slightly lower portion of environmental impacts for **System B** when compared with **System A**. From the environmental score results presented in Section 6.2.1, the introduction of low flush interventions (reducing water consumption 18%) results in overall impact score reduction of factor of magnitude ~ 10 (1.16E+01).

In **System C**, the construction of the **System A**ccounted for the largest portion of the environmental impacts across most impact categories. In particular, the anaerobic baffled reactor accounts for a significant portion of the environmental impacts. Within

the ABR, reinforcing steel and cast iron manhole covers are the primary contributors to environmental impacts for this process. In order to manufacture cast iron and steel, large amounts of electricity are required. In a South African context, thermal energy generated in the burning of coal produces the majority of South Africa's electricity.

Regarding the normalised impact assessment results, it was established that the significant impact categories included marine and freshwater aquatic ecotoxicity, eutrophication, global warming. When including the sewer network, wastewater conveyance is a major contributor to the most significant impact category (marine aquatic ecotoxicity). The reason for this major contribution is linked to the relatively large amount of energy required to produce potable water for domestic use. Marine aquatic ecotoxicity stems from the emission of heavy metals during the disposal of coal mining spoil. However, when excluding the sewer network and potable water supply from the system boundaries, construction is the primary contributor to marine aquatic ecotoxicity. The reason for this major contribution is once again related to the large amount of electricity required to manufacture cast iron and steel used for the ABR unit. Regarding eutrophication, direct discharge from irrigation is the primary contributor to this important impact category. More specifically, the incomplete removal of nutrients in the final effluent are primarily responsible for eutrophication. The release of methane during anaerobic processes in the settling unit and ABR are primarily responsible for global warming.

It is both relevant and important to mention the holistic nature of LCA which allows us to see impacts that are not obvious but are interlinked. More specifically to this study, pollution can be transported over a considerable distance and cause environmental impacts at a geographic location in an entirely different ecosystem. Marine aquatic ecotoxicity showed to be an important impact category in the normalised impact assessment results. Geographically, the NLM DEWATS is located approximately 7 kilometres from the coastline, however, the results demonstrated that that marine aquatic ecotoxicity was a significant impact category to consider.

6.5. General Discussion

6.5.1. Overview

The previous sections that were presented show the LCIA results of this study aligned to the goal and scope presented in **Chapter 4**. A number of assumptions and estimations were made due to the lack of product and site specific data for NLM DEWATS, nevertheless, a comprehensive set of results for the NLM DEWATS and the sewer network that discharges into the NLM DEWATS were produced. The results are aimed at providing relevant decision makers, design engineers and planners in order to make more informed decisions regarding the implementation of DEWATS within eThekwini Municipality. The goal of this study is not to compare the DEWATS with other sanitation systems, it is to establish environmental information regarding various sub-processes and phases (construction and O&M) associated with the DEWATS in order to identify areas of improvement. Effluent quality was not included in significant detail in this study since comparison with other sanitation systems was not the goal. When comparing a particular sanitation system with others, effluent quality is a very important parameter to consider in the analysis (Roux et al., 2010), since for the same inputs each wastewater treatment system considered will likely produce different outputs. The results presented in **Section 6.2** and **Section 6.3** highlights the importance of domestic water consumption, reinforcing steel and cast iron as significant inputs to the overall environmental impacts associated with the NLM DEWATS. Therefore, the discussions that are presented in the passages that follow are centred in the aforementioned system inputs.

6.5.2. Domestic Water Discussion

For **System A** and **System B** which both include wastewater conveyance to NLM DEWATS, domestic water consumption (for both flushwater and greywater) accounts for the largest portion of the environmental impacts across most impact categories. This particular input and its influence on the model will be presented in this section.

i) Water Consumption

Shown in **Figure 53** is a graphical representation of the domestic water consumption for both **System A** and **System B**. The assumptions regarding the calculations for water consumption in both scenarios was detailed previously in Chapter 4. As

mentioned in the system descriptions, **System A** assumes an 8 litre flush was used per flush event. **System B** assumes a low flush 2 litre system was used per flush event. For both systems, the same amount of greywater was assumed to be generated. Comparing **System B** to **System A**, the total daily water reduction amounts to 6570 litres per day and 18% of the total water consumption. The environmental consequence of this water saving is discussed in the following section. The portion of greywater to blackwater assumed for the calculations in this study were based on estimations provided by BORDA engineers. The assumption for **System A** in this study was that 24% of water consumption is allocated to flushwater and that 76% is allocated to greywater consumption. The assumption of 24% for flushing is very similar to the portion of flushwater assumed by the eThekwini Municipality for middle income households (eThekwini Municipality, 2009) as well as the portion of flushwater assumed by the Environment Agency (2011) and a study undertaken by Kobayashi et al. (2020). Reynaud and Buckley (2015), studied the per capita wastewater production of households connected to DEWATS. The study investigated the per capita demand of twenty-four systems over a period of five years. The results of the study showed the per capita wastewater production varied from site to site, however, an average per capita wastewater production rate of 81 l/c/d was recorded. In the base scenario (**System A**), the per capita demand for NLM is 86 l/c/d and in the low flush scenario (**System B**) the per capita demand is reduced to 71 l/c/d.

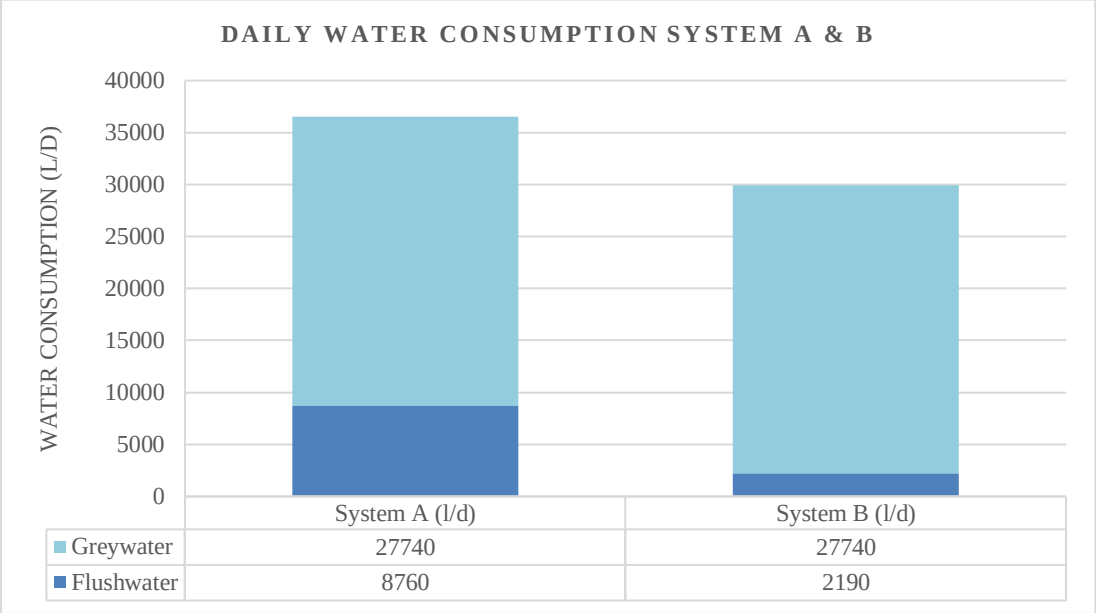

Figure 53: Graphical representation of water consumption for System A and System B

Although low flush systems have the capability to reduce domestic water consumption, greywater accounts for a significantly larger amount of daily water consumption (Environment Agency, 2011, eThekwini Municipality, 2009). In order to reduce the overall amount of domestic water consumption, further emphasis and efforts are required to reduce the quantity of greywater that is generated. The eThekwini Municipality makes several suggestions regarding the measures consumers can make in order to reduce the amount of greywater generated (eThekwini Municipality, 2009).

ii) Water Consumption and Environmental Impacts

Shown in **Table 16** is the relative contribution of domestic water consumption to environmental impact categories for **System A** and **System B**. As shown in the key on the right-hand side of **Table 16**, the cells (combination of **System A**nd impact category) highlighted in red are associated with a contribution of greater than 66 %, cells highlighted with yellow are associated with a contribution of between 33 % and 66 % and lastly green cells represent a contribution of less than 33 %. As seen below, the spread of results shows that 32 % overall are highlighted red (greater than 66 %), 41 % overall are highlighted yellow (between 33 % and 66 %) and 27 % are highlighted green (less than 33 %).

Table 16: Relative contribution of domestic water consumption to environmental impacts for System A and System B

	Relative Contribution of Domestic Water Consumption to Impact Categories (%)			
Impact Category	**System A - Base Scenario**	**System B - Low Flush**	**% Reduction of Impacts (A to B)**	**Key**
Abiotic depletion	55,01	48,25	6,76	Greater than 66%
Abiotic depletion (fossil fuels)	67,33	62,98	4,35	Between 33% and 66%
Global warming (GWP100a)	22,62	25,58	-2,95	Less than 33%
Ozone layer depletion (ODP)	97,98	97,48	0,5	
Human toxicity	53,20	47,27	5,93	
Fresh water aquatic ecotox.	67,05	61,59	5,46	
Marine aquatic ecotoxicity	70,65	65,04	5,61	
Terrestrial ecotoxicity	62,41	53,47	8,94	
Photochemical oxidation	21,17	24,26	-3,1	
Acidification	83,82	87,74	-3,92	
Eutrophication	2,94	5,6	-2,67	

iii) Implications on Sanitation

In **Section 2.7** of this study, several studies were presented that investigated a means to reduce the dependency on municipal water. Of the studies shown that investigated the use of household level rainwater harvesting systems, the systems that made use of rainwater harvesting and required a local pump to supply rainwater to toilet cisterns produced both poorer environmental results (typically related to energy consumption) and were not economically justified (Anand and Apul, 2011, Crettaz et al., 1999, Gao et al., 2017). The reason for the worsened environmental performance is due to increased energy requirements. In the studies considered in the literature review of this study, none of which investigated the option of rainwater harvesting systems that fed toilet cisterns via gravity. It is important to mention that the lowered energy requirements of a gravity fed system may result in a better overall environmental performance and hence further investigation should be considered for this option in future study. However, it must be mentioned that each application is case specific and in some cases gravity supply is not a feasible means of conveying rainwater to

cisterns due to site and topographical constraints. Recommendations made by relevant studies suggested using low flush technologies to reduce the amount of potable water being used at household level. Low flush interventions for this particular study resulted in average environmental impact reductions by a factor ~10.

Moreover, other studies considered the reuse of greywater as a means to reduce the reliance on potable water demand (Kobayashi et al., 2020). The study showed community reuse of greywater resulted in a better environmental profile than reuse at household level. Moreover, the study also showed that the environmental performance of the studied systems improved with the increase in amount of greywater used across different applications. In order to reuse across multiple applications, however, a treatment method needs to be selected that treats the greywater to the required standard for a given application. It is also important to mention that if source separated treatment systems were considered for application (greywater and blackwater treated separately), some important design aspects need to be considered. The influence of collecting blackwater separately is increasing the solids concentration in the sewerage network. Inadequate provision of pipe grades may result in solids settling and accumulation if self-cleansing velocities are not maintained in the pipes. Moreover, the change in influent quality may require adjustments of the wastewater treatment plant design (Kobayashi et al., 2020).

The environmental performance of potable water production has been previously studied in a local context (Friedrich, 2001). The environmental performance of the NLM DEWATS has shown to be largely influenced by upstream processes in the production and supply of potable water. Friedrich (2001), showed that the environmental performance of domestic water production is influenced by large energy requirements at the water treatment plant. Therefore, to improve the environmental performance of NLM DEWATS, it is important to consider interventions for the potable water treatment and supply as well as at the NLM DEWATS itself.

6.5.3. Infrastructure Discussion

Infrastructure for all three systems investigated showed to be a significant contributor to environmental impacts across most impact categories. When considering the environmental impacts of the NLM DEWATS, excluding the sewer network and domestic water required to convey the wastewater to the site (**System C**), infrastructure is the most significant input.

i) Materials Discussion

As previously mentioned in Section 4.5, the design period assumed in this study is 20 years and all construction materials are assumed to last the design period. However, it is important to note that if a longer period was assumed, materials would often not be considered to last the duration of the design period and replacement of materials will be included in the life cycle inventory phase of the analysis. The results presented in this study by individual input (**Figure 37, Figure 41** and **Figure 45**) demonstrate that four construction material inputs account for most of the environmental impacts associated with infrastructure. The construction material inputs alluded to are reinforcing steel, cast iron, concrete and brick. It was shown that the thermoplastic materials (PVC-U, HDPE, LLDPE) used in the construction of the NLM DEWATS were insignificant when compared with other construction materials. In particular, it was shown that reinforcing steel was the most significant contributor to environmental impacts across most impact categories.

ii) Infrastructure and Environmental Impacts

Shown in **Table 17** is the relative contribution of infrastructure to environmental impacts for all the scenarios investigated. Similar to the discussion and **Table 16** presented for domestic water consumption, the cells highlighted in red are associated with a contribution of greater than 66%, cells highlighted with yellow are associated with a contribution of between 33% and 66% and lastly green cells represent a contribution of less than 33%. **Table 17** shows that for **System A**, infrastructure contributes less than 33% for eight of the eleven impact categories and contributes between 33% and 66% for three impact categories. For **System B**, infrastructure contributes less than 33% for seven of the eleven impact categories and between 33% and 66% for four of the eleven impact categories. Lastly, for **System C**, infrastructure

contributes less than 33% for four impact categories, between 33% and 66% for two impact categories and greater than 66% for five impact categories.

When considering the results presented in **Table 17**, it is important to note the fact that wastewater conveyance and domestic water consumption is not included in **System C**. Therefore, **Table 17** demonstrates that when wastewater conveyance is included in the analysis, domestic water consumption carries the bulk of the environmental impacts across most impact categories and that infrastructure contributes significantly. However, when wastewater conveyance and domestic water consumption is not included, infrastructure accounts for the largest portion of environmental impacts across several impact categories. Most importantly, in **System C**, infrastructure accounts for the largest contribution to freshwater aquatic ecotoxicity which is the most significant impact category in the environmental profile presented in **Section 6.3.**

Table 17: Relative contribution of infrastructure to environmental impacts for systems investigated

	Relative Contribution of Infrastructure to Impact Categories (%)			
Impact Category	**System A - Base Scenario**	**System B - Low Flush**	**System C - Excluding conveyance**	**Key**
Abiotic depletion	43,22	50,77	96,35	More than 66%
Abiotic depletion (fossil fuels)	23,78	26,61	54,34	Between 33% and 66%
Global warming (GWP100a)	10,26	15,512	9,11	Less than 33%
Ozone layer depletion (ODP)	1,15	1,43	41,10	
Human toxicity	44,34	50,88	92,97	
Fresh water aquatic ecotox.	28,66	33,82	77,33	
Marine aquatic ecotoxicity	25,24	30,47	78,40	
Terrestrial ecotoxicity	36,49	45,55	93,16	
Photochemical oxidation	14,53	18,07	10,59	
Acidification	7,41	-17	-34	
Eutrophication	0,81	1,78	0,76	

6.6. Comparison of Results with Previous Studies

A series of international LCA studies were undertaken as presented in the literature review. For the current research the ones undertaken by Roux et al. (2011), Frances et al. (2012), Machado et al. (2007), Lopsik (2012) and Opher and Friedler (2016) have been used for comparisons.

6.6.1. Impact of the Sewer Network

Two studies discussed in the literature review of this dissertation considered the sewer network within the boundaries of their LCA study. Frances (2012), compared the environmental performance of a conventional wastewater treatment plant with a BORDA DEWATS plant. Although this particular study included the sewer network in the scope of the study, the sewer network (or wastewater conveyance process) was not isolated in order to demonstrate its environmental impacts. Only several results were shown and discussed in detail that are directly linked to the sewerage network. These values are shown in **Table 18**. However, it was observed that the contribution of the sewer system construction to the overall construction impacts was significant in this study (Frances, 2012). Roux et al. (2010), undertook an LCA study in order to compare the environmental performance of a VFCW and a conventional activated sludge wastewater treatment works. More interestingly, in this study, the influence of the sewer network was isolated to show its significance when compared with the main contributors to environmental impacts. **Table 18** shows a comparison of the results for all impact categories included.

Table 18: Selected values for environmental impacts associated with sewerage conveyance

Environmental Impacts Associated with Sewerage Conveyance in Selected Studies				
Environmental Impact Indicator	Current Study [%]	Roux et al. (2010) [%]	Frances et al. (2012) [%]	% Difference (Roux et al. and Current)
Abiotic Depletion	76.7	80	-	4
Acidification	83.4	75	-	11
Eutrophication	3.3	0	0	3
GWP	27.9	23	<5	21
Ozone Depletion	98.5	77	-	28
Human Toxicity	76.5	95	88%	19

Freshwater Aquatic Ecotoxicity	82.6	92	-	10
Marine Aquatic Ecotoxicity	82.5	87	-	5
Terrestrial Ecotoxicity	89.2	85	-	5

The current study values shown in **Table 18** reflect the impact assessment results for **System A** and refer to the impacts associated with the wastewater conveyance system. For further information of these, refer back to **Figure 39** to view the results. For the results shown in the **Table 18** for the study undertaken by Roux et al. (2010), impact assessment results for the VFCW are shown. Lastly, the results shown in Table 20 for Frances (2012), the values refer to percentages found in the text for **System B3** of their study since this configuration was most similar to this study. The results of this study are similar to the findings of Roux et al. (2010) and vary by an average of 12% overall. The most substantial difference shown in the results is ozone depletion which reflects a difference of 28%. Of the results available for the study undertaken by Frances (2012) only three direct results were shown in the text for comparison. The average difference of these three percentages is shown to be 12.5%.

Each of the compared systems shown in **Table 18** treat wastewater from a relatively similar number of inhabitants. The current study collects wastewater from approximately 420 inhabitants, Frances et al. (2012) consider 705 inhabitants in their DEWATS LCA study and Roux et al. (2010) VFCW system treated wastewater from 967 inhabitants. All systems are considered small scale decentralised systems and hence should allow for relatively even comparison. The size of the system treated is very important when making comparison (Kobayashi et al., 2020). Kobayashi et al. (2020) compared a number of greywater treatment systems at varying levels of implementation including community, neighbourhood and household level. The results for implementing sanitation systems at community level showed to be outperform household and neighbourhood systems. The reason for this is the larger construction requirements to treat greywater at household level and since the community system benefits from economies of scale (Kobayashi et al., 2020).

6.6.2. Major Impact Categories

Based on the normalised life cycle assessment results it is important to determine, on a relative basis, the environmental impact categories that appear to be more significant. **Section 6.3** of this dissertation presented normalised impact assessment results which indicate the environmental profile of the systems investigated. The following passages discuss the significant environmental impact categories as observed in the impact assessment results and compares the results with previous studies.

i) Marine aquatic ecotoxicity

As mentioned previously in **Section 6.3**, marine aquatic ecotoxicity proved to be the most significant impact category when considering the environmental profile for the systems investigated. Shown in **Appendix G** are the network diagrams for **System A** (**Appendix G-1**), **System B** (**Appendix G-2**) and **System C** (**Appendix G-3**) illustrating marine aquatic ecotoxicity contributions.

Referring to **Appendix H-1** and **Appendix H-2**, the process network diagrams demonstrate the major contribution of domestic water consumption to marine aquatic ecotoxicity. In the production of domestic water, electricity is the major component that results in environmental impacts. More specifically, South Africa's electricity is predominantly produced from thermal power generated from the burning of coal. Marine aquatic ecotoxicity is mainly due to heavy metals emitted to water bodies from the disposal of coal mining spoils. For **System A**, domestic water consumption accounts for 70.6% of the impacts, similarly in **System B** domestic water consumption accounts for 65% of environmental impacts to marine aquatic ecotoxicity. This slight reduction in environmental impacts shown from **System A** compared with **System B** is due to a lesser amount of potable water required.

The other notable contributor to the marine aquatic ecotoxicity impact category is cast iron and reinforcing steel. Cast iron accounts for 10.2% of the impacts in **System A** and 12.5% in **System B**. For **System C**, however, the major contributors to marine aquatic ecotoxicity are reinforcing steel (31.5%) and cast iron (14.1%). When comparing the environmental profiles of **System A** (**Figure 49**) and **System C** (**Figure 51**), **System A** has a considerably larger impact on marine aquatic

ecotoxicity. The difference between **System A** and **System C** in this regard is because **System C** does not include the wastewater conveyance process and hence domestic water consumption. The production of cast iron and steel is highly energy intensive. Marine aquatic ecotoxicity also stems from the emission of heavy metals from the disposal of coal mining spoils.

Marine aquatic ecotoxicity showed to be a significant impact category in a number of studies included in the literature review (**Chapter 2**) of this study (Lopsik, 2013, Opher and Friedler, 2016, Roux et al., 2010). In Opher and Friedler's (2016) study, a broad scope of processes was considered. More precisely, the desalination process was considered to contribute most to marine aquatic ecotoxicity due to the large energy requirements of desalination. This particular impact category was also related to processes in the supply chain of electricity. Similarly, the normalised results shown in Lopsik (2012) also demonstrate the significance of marine aquatic ecotoxicity and that the significance of this impact category is related to landfilling of ash for electricity production. In Roux et al. (2010), marine aquatic ecotoxicity showed to the largest environmental impact in their normalised results. However, an explanation for the prevalence of marine aquatic ecotoxicity was not elaborated in their study.

ii) Eutrophication

Eutrophication has shown to be a considerable environmental impact associated with wastewater treatment and sanitation systems. Along with global warming, eutrophication is the most commonly used impact category in wastewater treatment related LCA's in developing countries (Gallego-Schmid and Tarpani, 2019). Shown in **Appendix H** are the network diagrams for **System A** (**Appendix H-1**), **System B** (**Appendix H-2**) and **System C** (**Appendix H-3**) illustrating eutrophication contributions.

Across all three systems, there are two primary contributors namely ammonia and phosphate discharge. Ammonia is the primary contributor to eutrophication with a minimum contribution of 64.9% (**System B**) and maximum contribution of 69.6% (**System C**). Phosphate also contributes significantly with a minimum contribution of 27.3% (**System B**) and maximum contribution of 29.3% (**System C**). Due to the incomplete removal of nutrients after final discharge, Eutrophication potential has

been shown to be a major environmental impact associated with DEWATS (Frances, 2012) and constructed wetlands (Machado et al., 2007, Roux et al., 2010). In Frances (2012), considering **System B3** (the most similar system to this current study), effluent discharges showed to contribute 100% to eutrophication when compared with 96% for **System A** of this study. Similarly, Machado et al. (2007) and Roux et al. (2010) assessment of constructed wetlands systems showed 100% contribution from effluent discharges to eutrophication. Lopsik (2012), however, showed a slightly lesser result with 87% of eutrophication related to effluent discharges. Lastly, although Opher and Friedler (2016) did not consider direct discharge of wastewater effluent to the environment (reuse and reclamation was modelled), wastewater leakages in the sewerage collection system was modelled. In all scenarios considered the portion of impacts related to collection grid leakages was approximately 60% (Opher and Friedler, 2016).

Regarding the comparison of other similar studies and normalised results, eutrophication showed to be significant in all studies that included a normalisation phase. Similar to this study, the contribution of eutrophication showed to be the second most significant normalised impact category in Roux et al. (2010) and Lopsik (2012). Overall, it can be said that the results of this study correlate well with the prevalence of eutrophication as an important impact category as shown in other studies considered in the literature review.

iii) Global Warming

As previously mentioned, in Gallego-Schmid and Tarpani's (2019) review WWT-related LCA studies in developing countries, global warming is one of the most commonly used impact indicators. Shown in **Appendix I** are the network diagrams for **System A** (**Appendix I-1**), **System B** (**Appendix I-2**) and **System C** (**Appendix I-3**) illustrating global warming contributions.

For **System A** and **System B**, which include the process of wastewater conveyance, there are three primary contributors to global warming as seen in **Appendix I-1** (**System A**) and **Appendix I-2** (**System B**). The three primary contributors include methane produced in the settling unit (digester), methane produced in the ABR and domestic water consumption. However, for simplicity, the total methane produced

will also be referred to (methane produced in both the settler and ABR). Domestic water accounts for 22.6% of impacts to global warming in **System A** and 25.6% of impacts to global warming in **System B**. As mentioned in previous discussions, the bulk of the impacts associated with domestic water consumption are due to electricity required in the production of domestic water. The largest contributor to global warming in **System A** and **System B** is total methane. Methane accounts for 40.7% of

the impacts in **System A** and accounts for 58.1% of the impacts in **System B**. A product of anaerobic digestion, which takes place in the settling unit and ABR, is methane. Lastly, **System C** excluded the process of wastewater conveyance and hence also domestic water consumption. For **System C**, methane production in the settler and ABR result in 89.6% of the impacts to the global warming impact category.

As mentioned in the previous section, Frances (2012) findings showed the overall significance of global warming in the environmental profile of a BORDA DEWATS plant in India. In this study, Frances (2012) considered both the scenarios of releasing methane into the atmosphere as well as the potential for using methane (biogas) as a renewable energy (cooking, heating, etc.). The former scenario resulted in a negative impact on the environment which was shown to be the most significant impact category for the BORDA DEWATS in the normalised impact assessment results (Frances, 2012). However, when considering the methane as a potential renewable energy, the global warming impact category demonstrated how the BORDA DEWATS system could provide environmental benefits. The environmental benefits of this scenario result from avoiding the release of methane into the environment and by utilizing methane as a renewable energy.

The first major difference between this study and the study undertaken by Frances (2012), is that in this study the option to reuse methane as a potential renewable energy was not investigated. NLM DEWATS was originally designed to facilitate the harvesting of biogas, however, leakages and complications ensued and hence currently NLM DEWATS does not harvest biogas. Secondly, Frances (2012), did not include marine aquatic ecotoxicity as an impact category. In this study, marine aquatic ecotoxicity appeared to be a major impact category in the normalised impact assessment results. The differences between the global warming results of this study

and that of Frances (2012), may originate from the assumptions and differences regarding methane production rates. Moreover, the lack of site specific normalisation and weighting values may also further contribute to inaccuracy of results (Gallego-Schmid and Tarpani, 2019).

6.6.3. Grouped Inputs Comparison

In order to determine the phase/s, in the life cycle of a product or service, which are responsible for the bulk of the environmental impacts, it is important to analyse the impact assessment results by groups or phases. In this study, the life cycle assessment results were presented by individual material inputs, by grouped inputs (phases), by process and construction and O&M. The reason for presenting the results from a number of different perspectives is to develop a more holistic representation of the inputs, processes and phases responsible for various environmental impacts. A number of similar studies (Frances, 2012, Machado et al., 2007, Roux et al., 2010) also included results which demonstrated the phases (grouped inputs) responsible for environmental impacts. The grouped inputs and phases considered in this study and various other studies will be discussed in the passages that follow.

Roux et al. (2010) compared main contributors dismantling, operation, construction, sewer network and discharges. The results from this study demonstrated the major contribution of the sewer network across all impact categories excluding eutrophication and to a lesser extent global warming. Discharges were the primary contributor to eutrophication and global warming (Roux et al., 2010). Moreover, across most impact categories, the operation of the plant was more significant than the construction of the plant. The results of this study compare well with the results presented by Roux et al. (2010). In this study, for **System A** and **System B**, wastewater conveyance and the sewer network were the major contributor to all impact categories except for global warming, Photochemical oxidation and eutrophication. Discharges were shown to be the primary contributor to global warming, photochemical oxidation and eutrophication. However, there are differences when comparing **System C** with the results of Roux et al. (2010). For **System C**, which excludes wastewater conveyance, infrastructure (construction) was shown to be a major contributor to most impact categories. In **System C**, discharges accounted for

the largest portion of the impacts to global warming. Photochemical oxidation and eutrophication and transportation was the major contributor to ozone layer depletion and acidification.

Similarly, Machado et al. (2007) compared the phases of construction, O&M and dismantling and disposal. Moreover, the results were presented for three separate systems including a slow infiltration rate system, constructed wetlands and an activated sludge treatment works. The constructed wetlands will be used for comparison and discussion. For the constructed wetlands LCA presented by Machado et al. (2007), the construction and assembly phase were responsible for the bulk of the environmental impacts for abiotic depletion, global warming, ozone layer depletion, photochemical oxidation. Only for eutrophication, O&M was the primary contributor. Dismantling and disposal appeared to have a much lesser impact than construction and O&M. Comparing the results of Machado et al. (2007) with this study, the results appear to be different to all systems investigated in this study. **System C** is the most similar to those seen in Machado et al. (2007) since construction was shown to have a major influence in most impact categories in **System C**. The reasons for this difference are due to the fact that water treatment and supply was not included within the **System B**oundaries for their study and hence the major power requirements associated with operation are not shown.

Lastly when comparing the phased results of this study with Frances (2012), the results demonstrate similar findings for the top three indicators including aquatic ecotoxicity, eutrophication potential and global warming potential. A difference of around 5% was seen for global warming when comparing **System A** of this study to **System B**3 of Frances (2012). A difference of 1% was shown for eutrophication and lastly a difference of 28.1% was shown for aquatic ecotoxicity for the same aforementioned systems.

6.7. Summary

This chapter presented the results of an LCA of the NLM DEWATS in Newlands KwaZulu-Natal. Initially, LCIA results were presented by showing the environmental impact scores for the investigated systems to understand the order of magnitude of

environmental impacts. Thereafter the results were presented in the form of stacked column graphs, showing the percentage contribution for each individual material input. The aforementioned individual inputs were then grouped into main input categories and phases and another set of stacked column graphs were presented showing the relative contribution to environmental impacts. Thereafter, the systems were modelled by process and the results were presented again in the form of stacked column charts showing the contribution the system processes have on the environmental impacts. Lastly, in terms of demonstrating relative percentage contributions, the systems were divided into construction and O&M and presented in the form of stacked column graphs. Thereafter, normalised results were presented to demonstrate the relative significance of environmental impact categories when compared with each other. A discussion regarding domestic water consumption and infrastructure was provided due to their overwhelming contributions to environmental impacts. Lastly a comparison of the results of this study with other relevant studies was provided.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

South Africa and many developing countries around the world are experiencing a lack of universal sanitation provision for their citizens. In order to combat the sanitation backlog, appropriate sanitation is necessary to uphold the health and dignity of those in need. Decentralised Wastewater Treatment Systems (DEWATS) are becoming widely recognized by authorities and city managers across the world as an alternative for providing wastewater treatment in densely populated low-income areas. DEWATS is a low technology, modular wastewater treatment system that aims to provide solutions not only in the technical and engineering realms of sanitation, but also to local economic and social domains. Important consideration and information are required for decision-makers to recommend the most appropriate sanitation solution for a given application. One of those factors to be considered is the environmental performance of the sanitation system.

Environmental Life Cycle Assessment (LCA) can be used as a tool to evaluate the potential environmental impact of the DEWATS at any stage of the treatment process. This research project involved an LCA study of the existing NLM DEWATS plant in Newlands KwaZulu-Natal. Three separate scenarios were modelled. Two of the systems modelled (**System A** and **System B**) included the existing sewer network and wastewater conveyance process. The base scenario was modelled as the current NLM DEWATS (**System A**), a scenario that utilized low flush (2 litre) toilets and the current NLM DEWATS (**System B**) and lastly a scenario was modelled excluding the sewer network (**System C**). The NLM DEWATS was not compared with alternative wastewater treatment technologies and therefore detailed discussions regarding treated effluent quality was not presented. The NLM DEWATS system was modelled under three separate scenarios in order to establish the significant contributors to environmental burdens. The purpose of undertaking such an analysis was to identify potential areas of improvement of the NLM DEWATS and make recommendations for relevant stakeholders, practitioners, engineers and planners. As such this research has achieved the aims and objectives as set out in **Chapter 1**.

This LCA study was undertaken in four phases as outlined in the guidelines set out by the ISO 14000 series of standards. Typical of most LCA studies, this study was divided into four sections including goal and scope definition, inventory analysis, impact assessment and interpretation. The goal and scope definition were presented in **Chapter 4**. The goal of this study was to determine the environmental impacts associated with the NLM DEWATS through the generation of environmental LCA scores using the CML midpoint method. The life cycle inventory phase was presented in **Chapter 5**. The inventory analysis phase involved the collection and processing of data for the operation and construction of the wastewater treatment system. Design reports, construction drawings, design data sheets, measurements and correspondence with engineers were required to facilitate the life cycle inventory. The system inputs were then scaled based on the functional unit. The life cycle impact assessment was presented in **Chapter 6** of this study. The impact assessment results were produced using SimaPro software and the data developed in the life cycle inventory phase. Moreover, the normalised results were calculated based on 1995 global reference values since local factors were not readily available this was the best option for the normalisation step. Lastly, the interpretation phase was presented in **Chapter 6** and **Chapter 7**.

When including the sewer network and wastewater conveyance in the system boundaries, domestic water consumption was observed to have the largest overall impact on the impact categories considered. A low flush scenario was considered in this study in order to determine the influence of reducing flushwater on the overall environmental profile. For the systems investigated, greywater accounted for a significantly larger portion of domestic water consumption than flushwater. Using a low flush intervention resulted in an overall reduction in wastewater generation of up to 18% which result in a dramatic improvement in the environmental performance of the system. By using a low flush intervention, the environmental impacts can be reduced by a factor of ~ 10 (1.16E+01). Domestic water showed to be a major influence on the environmental performance and water consumption itself is an important consideration in a local context.

Infrastructure was shown to be a significant input when excluding the sewer network and wastewater conveyance from the **System B** boundaries. Four construction materials were primarily responsible for the environmental impacts including reinforcing steel, cast iron, concrete and brick. The most significant of these aforementioned materials was reinforcing steel. The results indicate that the operation phase is responsible for the largest portion of environmental impacts when including wastewater conveyance (**System A** and **System B**). However, when excluding the sewer network (**System C**) and wastewater conveyance, O&M and construction share a relatively even share of the environmental burden. Therefore, wastewater conveyance is an important part and the first component to be targeted for improvements.

7.2. Recommendations

7.2.1. Recommendations for Environmental Improvement

As demonstrated in the results of this study, domestic water consumption accounted for a large portion of the environmental burdens. In the case of this current study, water savings of approximately 18% from low flush interventions resulted in a factor of ~10 (1.16E+01) reduction across impact categories. This is significant improvement in environmental performance and low flush interventions at household level should considered as an important intervention to improve the environmental performance. Since the portion of water demand required for toilet flushing is only in the order of 25%, further measures for reducing dependency on municipal water should also be investigated. Another potential method for doing this is to separately collect and treat greywater for further reuse. Separate greywater treatment and reuse at a community level is a potential means to improve the environmental performance of the system.

In relation to the domestic water referred to in this study, the source of environmental impact originates from large energy requirements originating at water treatment works. Energy minimisation strategies and techniques such as pump efficiency can be implemented in the design of the water treatment facilities in order to reduce the environmental burden of domestic water production. Recommendations to improve the environmental performance of the system are related to improving efficiency of

mechanical treatment equipment and pumps. Water treatment is, however, a separate system altogether which has been investigated in literature and is outside of the scope of this study. Another important point to mention is South Africa's electricity mix. A shift away from the majority use of burning coal to produce thermal energy for electricity towards renewable energy could potentially provide a means to further improve the environmental performance of both potable water production and NLM DEWATS.

Infrastructure was also identified as an important contributor to environmental impacts associated with the NLM DEWATS. In particular, reinforcing steel and cast iron accounted for a large portion of environmental burdens. A suitable alternative for reinforcing steel that displays similar properties is not currently on the market. Cast iron manhole covers are used throughout the NLM DEWATS plant and are the primary cast iron constituent reflecting in the life cycle inventory. Polymer manhole covers are a suitable alternative which are widely available on the market. The findings of this study showed that thermoplastic materials (used for pipes and tanks) accounted for an almost negligible portion of the environmental burden and hence polymer manholes may be beneficial.

The use of biogas harvesting systems or flaring of methane may largely reduce the extent of global warming associated with the NLM DEWATS. However, the provision of biogas harvesting systems is not always suitable. The system requires a large amount of organic matter and the proper installation of the system is of utmost importance.

7.2.2. Recommendations for Improvements to this Study

In order to validate results, it is often common practice among LCA practitioners to apply the life cycle inventory to two or more separate impact assessment methodologies. Further research is required to validate the results of this study using at least two life cycle impact assessment methodologies. Moreover, the usage of impact assessment categories that may more accurately reflect the local context would greatly improve the accuracy of the results of this study.

Further system improvements could be modelled as separate scenarios and compared against a base scenario. The separate collection and treatment of greywater with reuse at community level could be investigated and compared with other interventions such as low flush toilets and rainwater harvesting (worst case scenario). The inclusion of methane flaring and/or biogas harvesting should be considered as an improvement scenario. Combinations of the aforementioned improvements should be modelled and compared against a base scenario.

7.2.3. Recommendations for Future Study

Based on the results of this study, low energy (gravity fed) rainwater harvesting systems in combination with low flush toilets is recommended for future research. Due to the large influence of electricity on the environmental burdens shown in this study, it is recommended further consideration is given to electricity production in a South African context. On that note, novel LCA studies that investigate the burden from the South African electricity production mix that consists of a larger proportion of renewable energy. This study may be aligned with South Africa's energy strategy for the upcoming years.

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APPENDICES

Appendix A: Overview of Roles and Responsibilities of Local Government and Related Institutions

Shown in **Figure A-1** is a diagram showing the roles and responsibilities of relevant stakeholders and related institutions in the water and sanitation sector in South Africa taken from DWAF's *The roles and Responsibilities of Local Government and Related Institutions*.

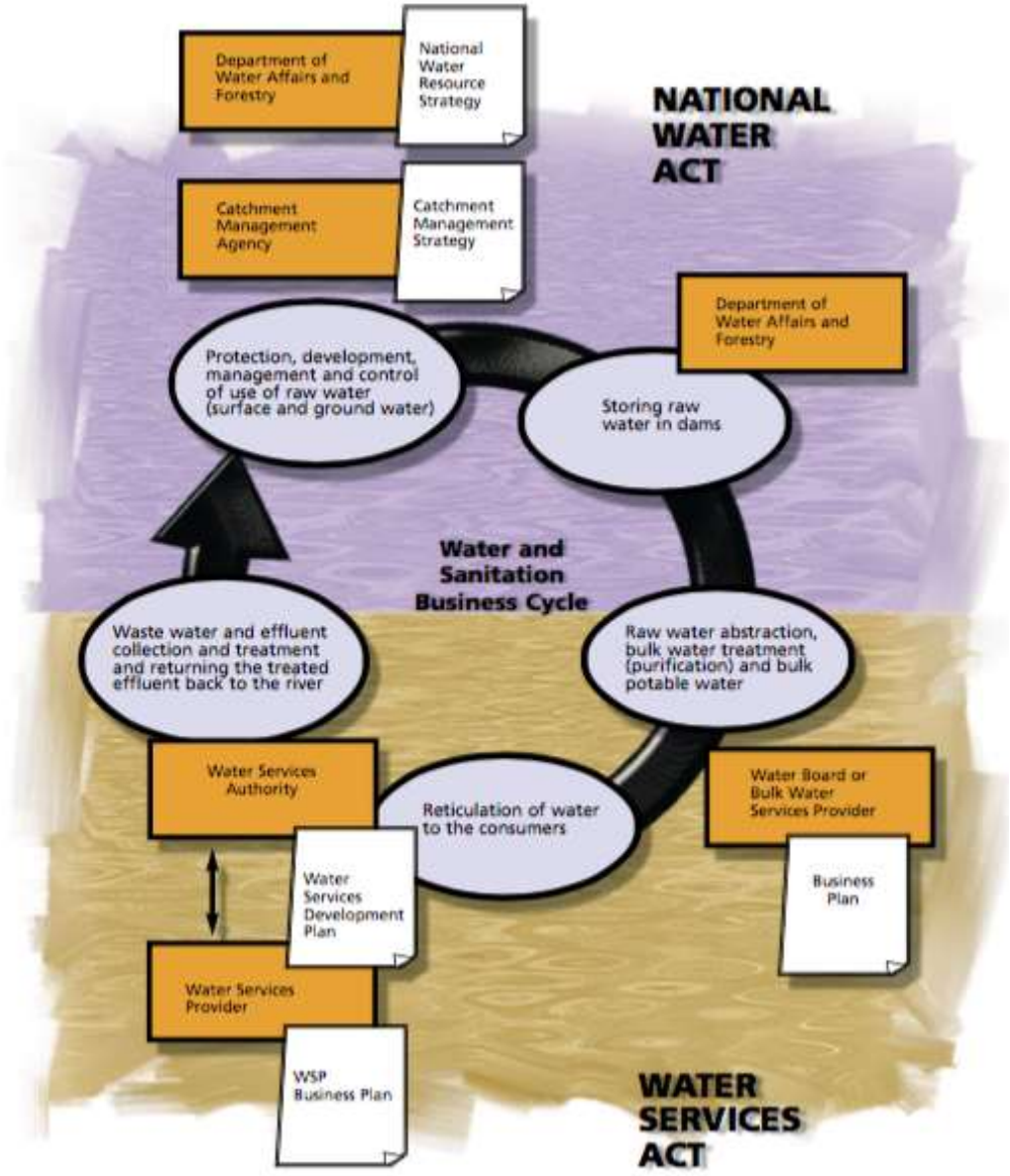

Figure A- 1: Overview of stakeholders and their responsibilities in the water and sanitation sector in South Africa (DWAF, 2005)

Appendix B: Related Acts, Policies, Strategies and Guidelines

According to the National Sanitation Policy of 2016, the following documents should be referred to in conjunction with the following existing national acts, policies, strategies and various sector guideline documents (Department of Water and Sanitation, 2016):

- The Constitution of the Republic of South Africa (Act 108 of 1996);
- The National Water Act (Act 36 of 1998);
- The Water Services Act (Act 108 of 1997);
- Regulations Relating to Compulsory National Standards and Measures to Conserve Water (General Notice 22355 of 8 June 2001) in terms of section 9 of the Water Services Act;
- The Strategic Framework for Water Services 2003;
- Local Government: Municipal Systems Act (Act 32 of 2000);
- Local Government: Municipal Structures Act (Act 117 of 1998);
- The National Health Act (Act No. 61 of 2003);
- National Environmental Management Waste Act (NEMWA) (Act 59 of 2008);
- National Environmental Management Act (NEMA), Act 107 of 1998;
- Framework for a Municipal Indigent Policy 2005;
- Guidelines for the Implementation of the National Indigent Policy on Water, Sanitation, Electricity / Energy and Waste Removal by Municipalities 2006;
- Municipal Infrastructure: Roles and Responsibilities of National, Sector Departments, Provincial Counterparts and Municipalities (Department of Co-operative Governance, 2006);
- The National Water Resources Strategy (2004);
- The Housing Act (Act 107 of 1997);
- the Department of Water Affairs Free Basic Water Implementation Strategy 2007;
- the Department of Water Affairs Free Basic Sanitation Implementation Strategy 2009;
- White Paper on Integrated Pollution and Waste Management for South Africa;

- National Waste Management Guideline for South Africa;
- National Guideline for Water Quality Management in Dense Settlements;
- Drinking Water Quality Management Framework for South Africa;
- Compulsory National Standards for the Quality of Potable Water (2001, Regulation 5 of Section 9 of the Water Services Act);
- Ensuring Water Services to Residents on Privately Owned Land: A Guide for Municipalities;
- The Department of Water Affairs Water Services Intermediary Explanatory Guideline;
- Local Government: Municipal Property Rates Act of 2004;
- Department of Labour Policy on Minimum Wages for Farm Workers;
- The Refugees Act (Act 130 of 1998);
- The White Paper on Disaster Management 1999;
- Water Supply and Sanitation Policy White Paper – November 1994;
- Water Policy White Paper – April 1997;
- Transformation of the Health System White Paper – April 1997;
- White Paper on Local Government – March 1998;
- White Paper on Environmental Management Policy – April 1999;
- Local Government Transition Act (Act 97 of 1996);
- Intergovernmental Fiscal Relations Act (Act 97 of 1997);
- The Intergovernmental Relations Framework Act, 2005 (Act No. 13 of 2005);
- The Local Government: Municipal Demarcation Act (Act 27 of 1998);
- The Public Finance Management Act (Act 1 of 1999);

i) Constitution of the Republic of South Africa

The Constitution of the Republic of South Africa (No. 108 of 1996), more specifically in Chapter 2: Bill of Rights, provides the right of all people in South Africa to dignity and the right of access to an environment which is not harmful to their health or well- being and is sustainable and protect from degradation and pollution. Although sanitation is not specifically stated, it is tacitly implied in the above rights. There are a number of further clauses in the Constitution that relate to sanitation which are outlined by Tissington (2011).

ii) White Paper on Basic Household Sanitation

The 1994 White Paper soon followed after the establishment of the RDP and outlined a number of policy principles. The main basis of the 1994 White Paper is that water services development should be "demand driven". Furthermore, the White Paper lays out the institutional framework for water and sanitation provision, which was finally legislated in the Water Services Act in 1997. With regard to financing, the White Paper of 1994 states that although sanitation services should be self-financing at a local and regional level, provisions should be made for poor communities that are unable to afford basic services. In such circumstances, government is to bare construction costs of basic minimum services, however, operation, maintenance and replacement costs arenot subsidised by government.

The principles of White Paper (1996) are echoed in the 2001 White Paper on Basic Household Sanitation. The 2001 White Paper creates the framework for the provision of sustainable sanitation in South Africa, focusing on households and regions that have lacked access to adequate sanitation in the past (mostly low density rural settlements and informal settlements). Similar to the 1996 White Paper, emphasis of the 2001 White Paper is on demand-driven sanitation provision. Furthermore, the 2001 White Paper strongly emphasises sanitation services provision to households in rural areas of the country.

iii) National Sanitation Policy

Following the release of the 1994 White Paper, the National Sanitation Policy (1996 – also a White Paper) was released and intended to resolve concerns raised in the 1994 White Paper. The National Sanitation Policy lists the main sanitation systems used in

South Africa and the technologies, which are deemed to not meet the policy's criteria for basic sanitation. The sanitation systems that were highlighted as inadequate included traditional unimproved pits, the bucket system and portable chemical toilets. Chemical portable toilets are not encouraged to be used, except in emergency situations (Tissington, 2011).

In 2016 the DWS published the *National Sanitation Policy 2016*. In this document, a number of gaps and challenges that were identified that require sanitation policy review, and subsequent legislative amendment. With regard to sanitation services principles, this document focuses on applying the principles of "polluter pays", "user pays" and increasing awareness of the economic benefits of sanitation (Department of Water and Sanitation, 2016).

iv) Acts

Two Acts that are outlined in Part 2 of DWAF's The Roles and Responsibilities of Local Government and Related Institutions include the Water Services Act (108 of 1997) and the National Water Act (36 of 1998). The Water Services Act (108 of 1997) and National Water Act (36 of 1998) presents the legislative framework within which water supply and sanitation services and water use are required to take place (DWAF, 2005). The purpose of the Water Services Act is to legislate the municipalities' responsibility of providing water supply and sanitation services. Furthermore, the primary objective of the Water Services Act is to aid municipalities to fulfil their role as a WSA, to uphold the best interests of consumers and to provide clarity regarding the role of other water institutions (water service providers and water boards). The National Water Act legislates the means in which water resource is "protected, used, developed, conserved, managed and controlled" (DWAF, 2005).

The purpose of the Housing Act 107 of 1997 is to provide for a sustainable housing development process, outlining the general principles applicable to all spheres of government, defining the roles of national, provincial and local governments in respect of housing development and to provide the basis for financing national housing programmes. Sanitation is relevant in this regard since sanitation is an imperative partof adequate housing (Tissington, 2011).

v) Strategies

The Strategic Framework for Water Services: Water is Life Sanitation is Dignity, developed by the South African Local Government Association (SALGA) and a wide range of stakeholders, was approved by Cabinet in 2003. This document presents an

extensive review of policies, legislation and strategies with regard to the provision of water services in South Africa. Contrary to the 2001 White Paper on Basic Household on Sanitation, which promoted a demand-responsive sanitation assistance programme, the Strategic Framework of 2003 focuses on sustainable servicing by municipalities anda supply-driven municipal provision programme (Tissington, 2011).

Due to a number of developments around sanitation *inter alia* the establishment of MIG (Municipal Infrastructure Grant) for Municipalities, the National Sanitation Strategy of 2005 was published. The objective outlined in this document is to eliminate the sanitation backlog by 2010 and discusses a number of key factors in sanitation governance including roles and responsibilities in sanitation delivery, planning, financing, implementation approaches and a number of others (Tissington, 2011). Although a focal point of the Strategic Framework for Water Services (2003) was the provision of Free Basic Sanitation (FBSan), it was only in March of 2009 that Free Basic Sanitation Implementation Strategy was approved. This Strategy was developed to assist WSAs in "providing all citizens with free basic sanitation by 2014".

Appendix C: Formal and Informal Sanitation Needs in South Africa

Taken from the DWA's s 2012 *Report on the Status of Sanitation Services in South Africa* is the percentage of sanitation needs for both formal and informal settlements in South Africa.

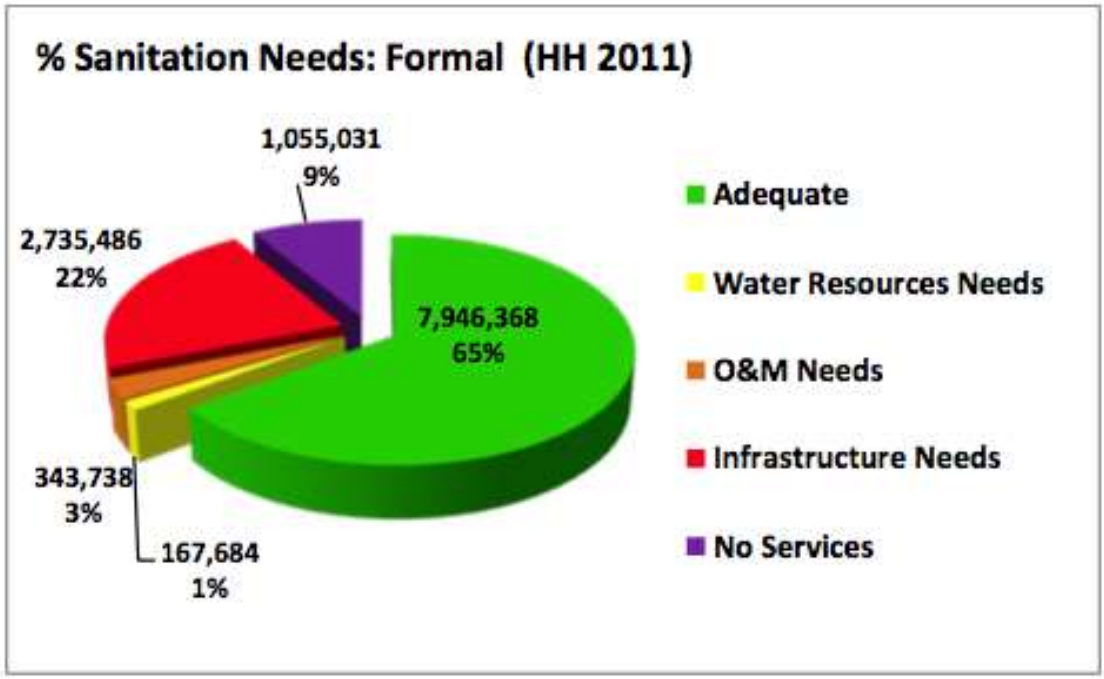

Figure C- 1: Formal Sanitation Needs in South Africa

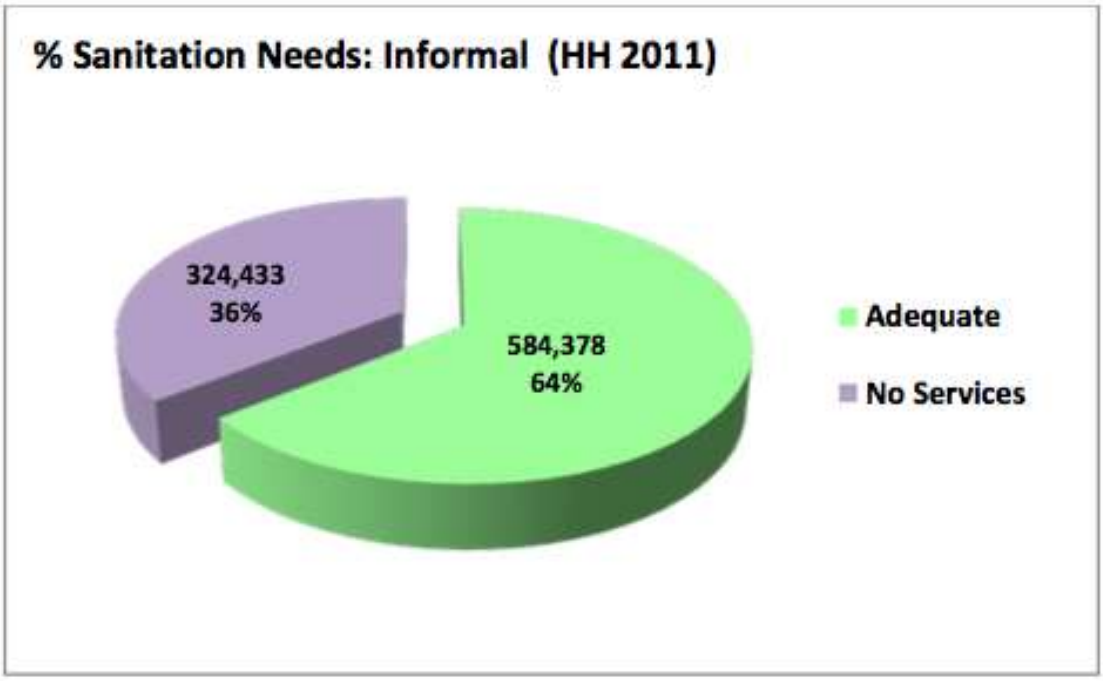

Figure C- 2: Informal Sanitation Need in South Africa

Appendix D: Informal Settlements in eThekwini Municipality

The eThekwini Municipality is located on the east coast of South Africa in the Province of KwaZulu-Natal. The eThekwini Municipality Area (EMA) has an area of approximately 2555km^2 and extends from Umkomaas in the South to Tongaat in the North and from the coastline in the East to Cato Ridge in the West (eThekwini Municipality, 2018). **Figure D-1** below shows the location and division of spatial planning regions in eThekini Municipality.

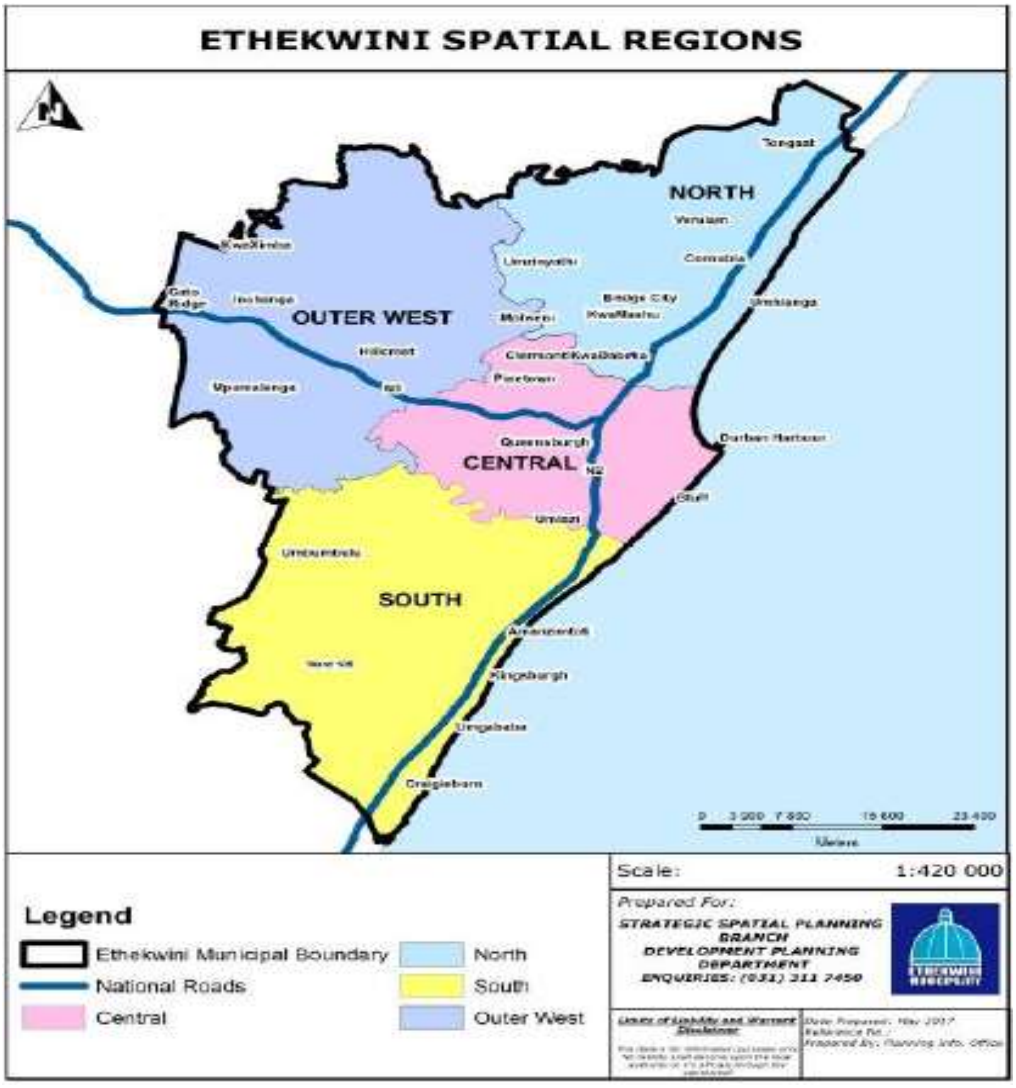

Figure D - 1: Location of eThekwini Municipality (eThekwini Municipality, 2018)

Appendix D-1: Demographic Profile

Table D-1 below shows a forecast of the population for eThekwini over five years. A census is normally undertaken by Statistics South Africa every 10 years and this provides a forecast based on fertility rate, life expectancy, mortality rates, HIV/AIDS and migration (eThekwini Municipality, 2018).

Table D- 1: Population forecast in eThekwini Municipality (Statistics South Africa, 2011)

Year	2016	2017	2018	2019	2020
Population Total	3,677,575	3,723,435	3,767,939	3,811,167	3,853,278

The gender profile of eThekwini Municipality is no different to other municipal areas and is divided by 49% male and 51% female population. The overall population of eThekwini is young with 63% of the population below the age of 35 years old. The 0-14 year's old age group makes up 29% and the 15-34 age group comprises 33% of the population (eThekwini Municipality, 2018).

Appendix D-2: Spatial Context and Informal Settlements

The land in eThekwini Municipality comprises of a multitude of land uses including informal, formal, rural and urban settlements which are supported by economic., transport, public and social infrastructure. Furthermore, traditional settlements, agriculture and the metropolitan open space system also make up a considerable amount of land (eThekwini Municipality, 2018). The abovementioned traditional settlements in rural areas form part of the Ingonyama Trust and presents numerous challenges with regard to urban management and service provision (eThekwini Municipality, 2018).

A large number of informal settlements are distributed amongst the city. A good portion of these settlements are located in peripheral locations or are on steep land or flood plains, which places them at risk of erosion and flood damage. **Figure D-2** shows the spread of informal settlements across the eThekwini Municipality. A

majority of the influx of migrants into the city gather on the city periphery and rural regions due to land affordability in traditionally owned rural areas and as a result of the segregated planning arrangements from the Apartheid era (eThekwini Municipality, 2018).

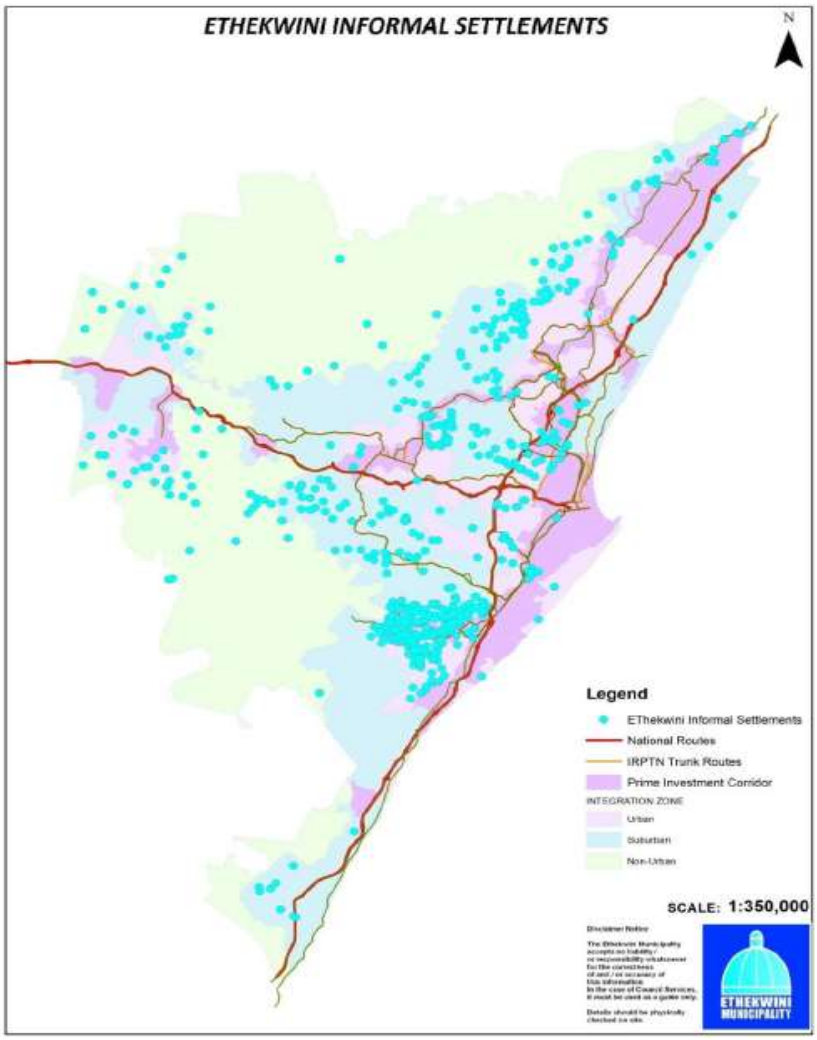

Figure D - 2: Informal settlements in eThekwini Municipality

Appendix E: Typical BORDA DEWATS Configuration

Shown in **Figure E-1** below are the components typically seen in a common BORDA DEWATS plant. The NLM DEWATS utilizes a settler for primary treatment, an anaerobic baffled reactor and anaerobic filter housed in a single unit for anaerobic digestion. Lastly, both a vertical flow and horizontal flow constructed wetlands are utilized for aerobic and facultative decomposition at the NLM DEWATS.

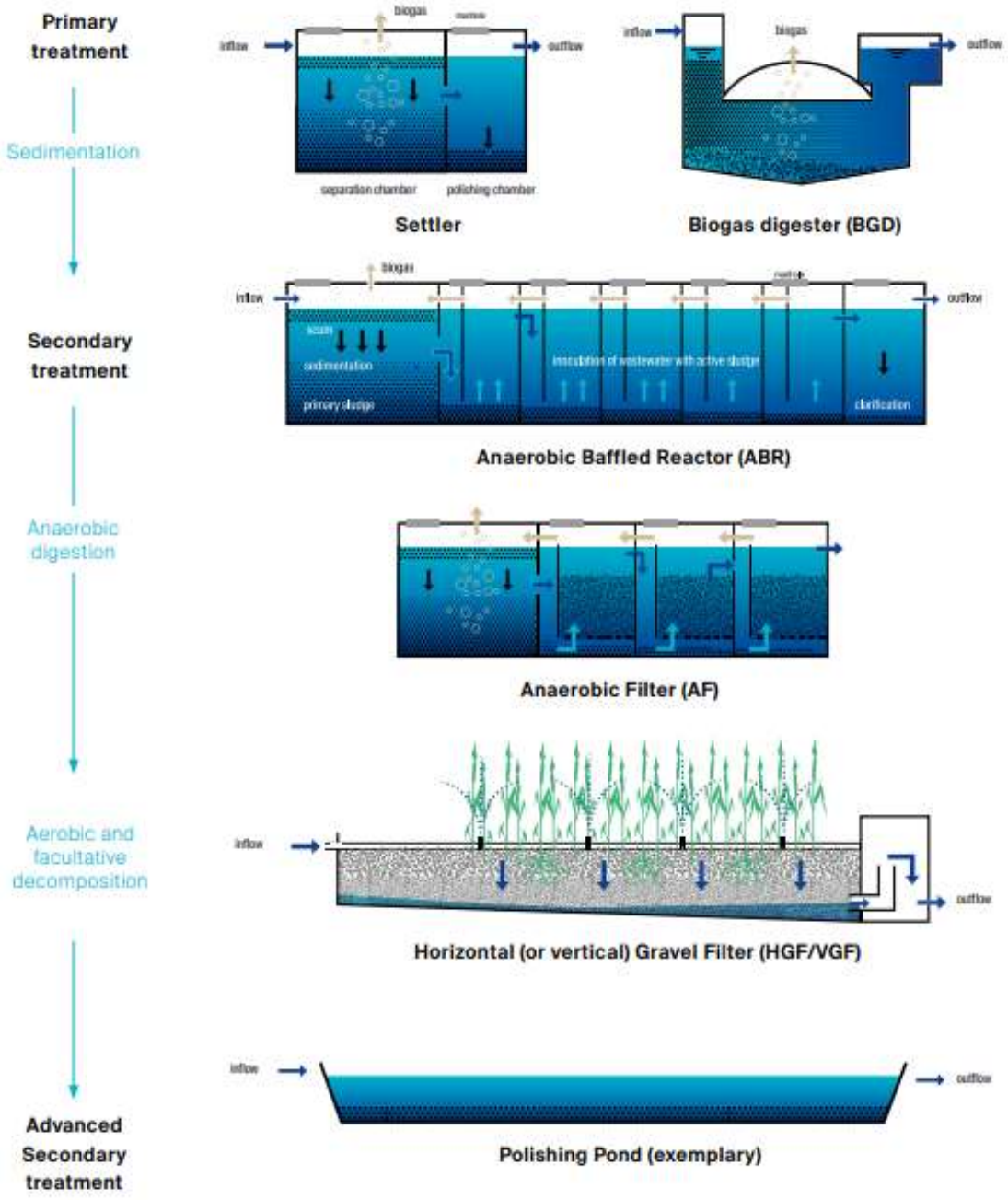

Figure E- 1: Typical BORDA DEWATS processes and components

Appendix F: Sewer network

Seen overleaf in **Figure F-1** is a topographical map showing the sewer network and households wherein wastewater is collected and transported to the NLM DEWATS. The information provided in the map overleaf was provided by engineers at the eThekwini Municipality. The sewer network shown overleaf comprises of approximately 1641 meters of PVC-U pipe. The external pipe diameters of this particular network is mostly 160mm. Concrete sewer manholes are found at all vertical and horizontal changes. The area marked in red was incorrectly shown as the site location for the NLM DEWATS. The NLM DEWATS site location is east of the to the east of the topographic map shown in **Figure F-1**.

Figure F- 1: Topographical map of NLM wastewater catchment area and sewer network

Appendix G: Marine Aquatic Ecotoxicity

Appendix G-1: Marine Aquatic Ecotoxicity System A

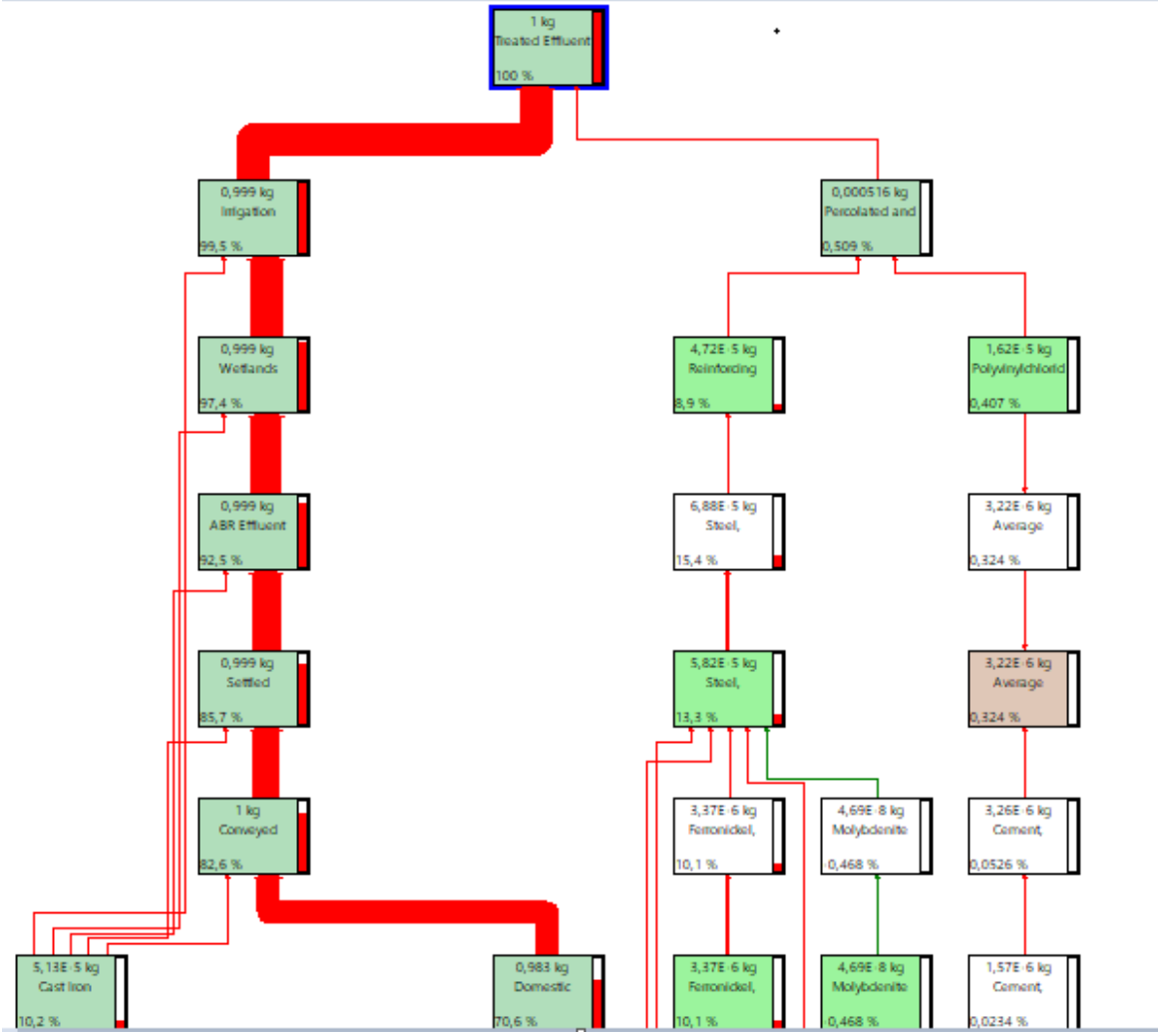

Figure G- 1: Process network diagram for System A illustrating Marine Aquatic Ecotoxicity contributions

Appendix G-2: Marine Aquatic Ecotoxicity System B

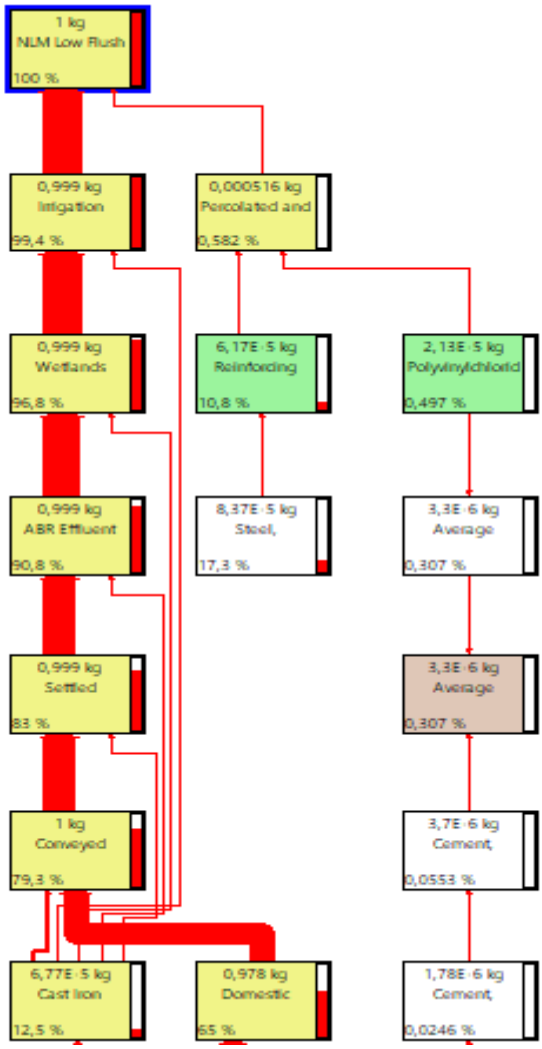

Figure G- 2: Process network diagram for System B illustrating Marine Aquatic Ecotoxicity contributions

Appendix G-3: Marine Aquatic Ecotoxicity System C

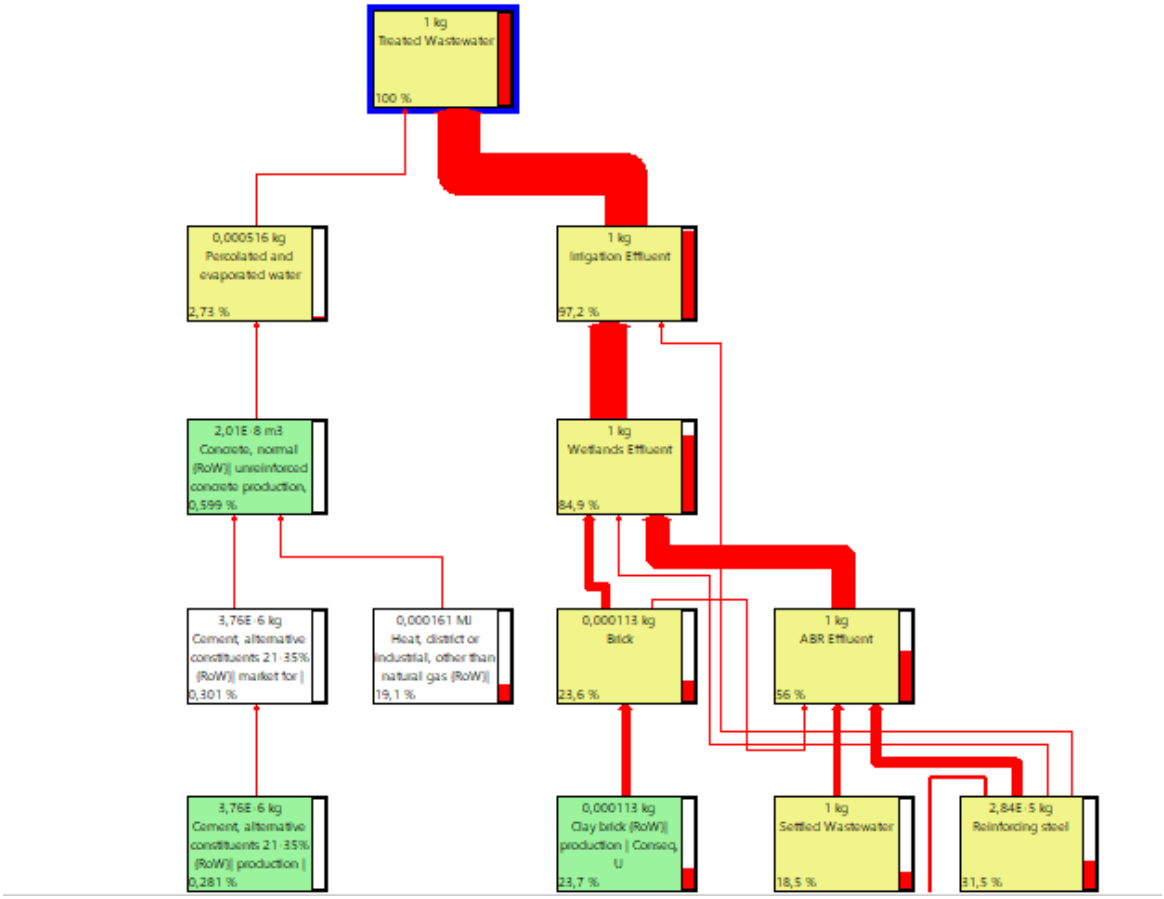

Figure G- 3: Process network diagram for System C illustrating Marine Aquatic Ecotoxicity contributions

Appendix H: Eutrophication

Appendix H-1: Eutrophication System A

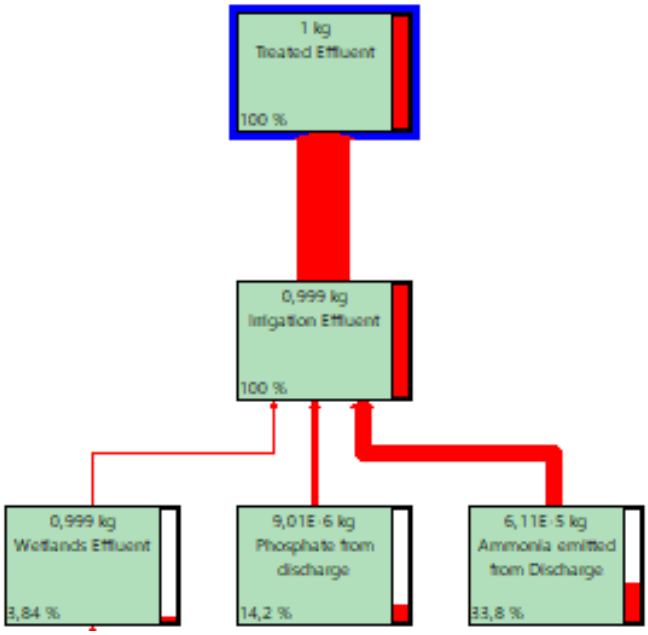

Figure H- 1: Process network diagram for System A illustrating Eutrophication contributions

Appendix H-2: Eutrophication System B

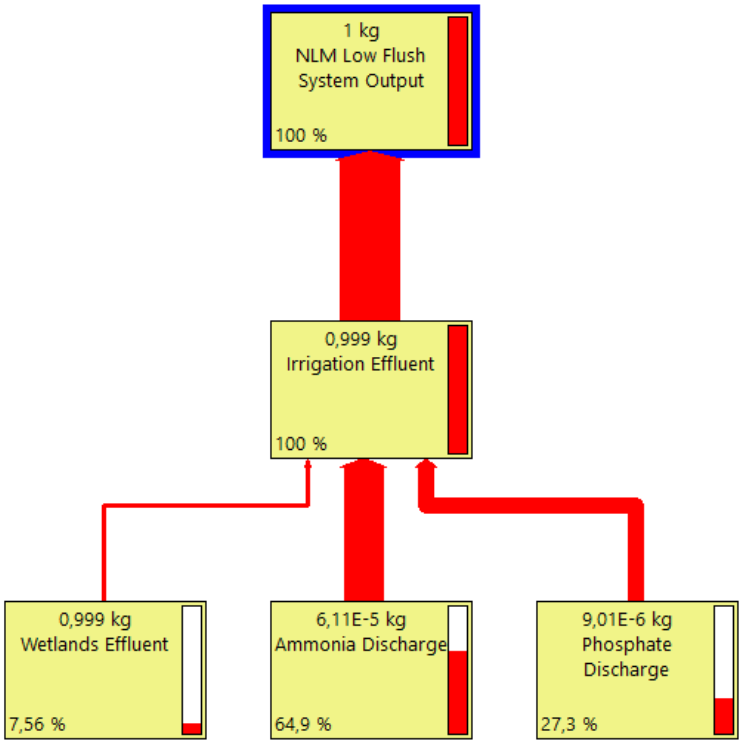

Figure H- 2: Process network diagram for System B illustrating Eutrophication contributions

Appendix H-3: Eutrophication System C

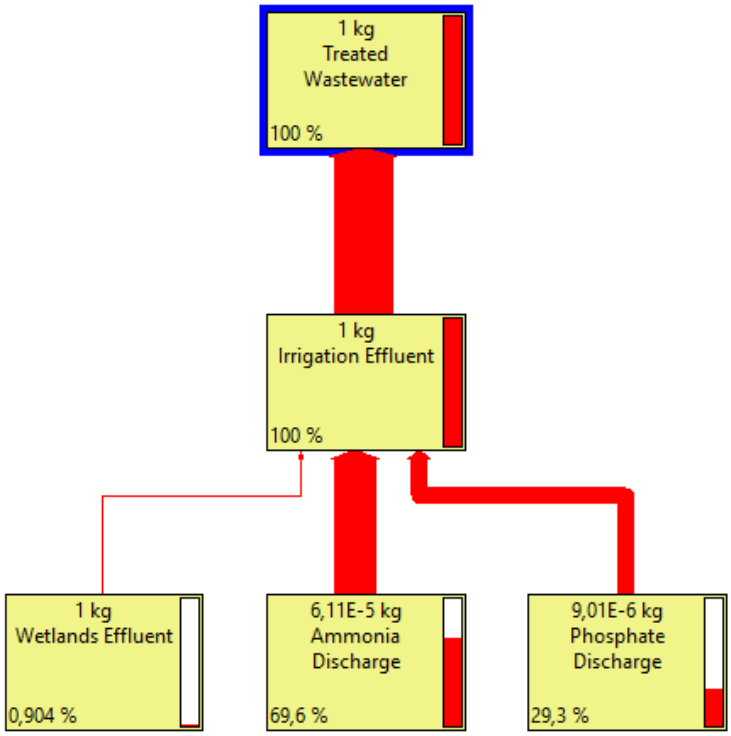

Figure H- 3: Process network diagram for System C illustrating Eutrophication contributions

Appendix I: Global Warming

Appendix I-1: Global Warming System A

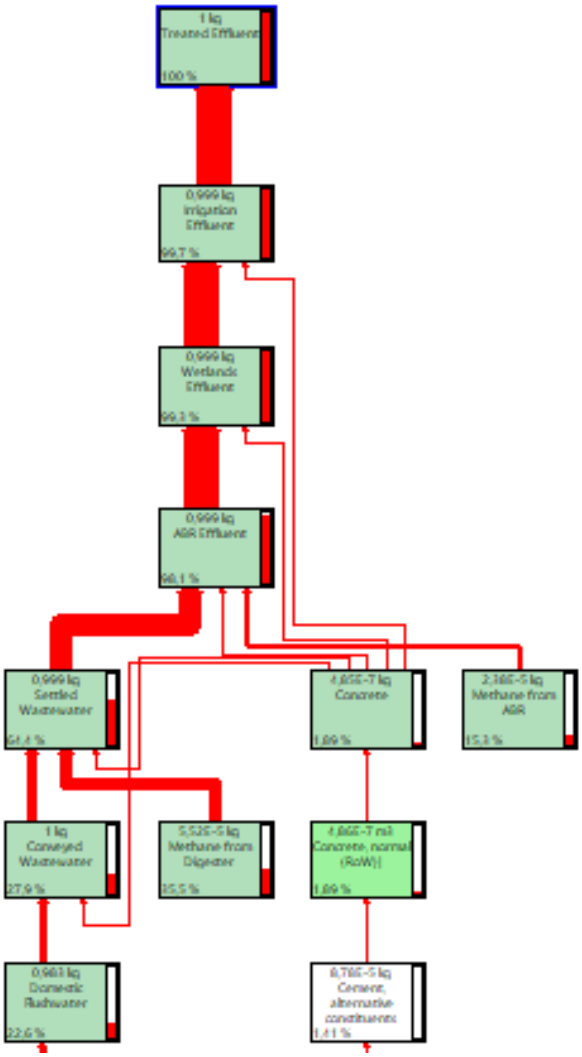

Figure I- 1: Process network diagram for System A illustrating Global warming contributions

Appendix I-2: Global Warming System B

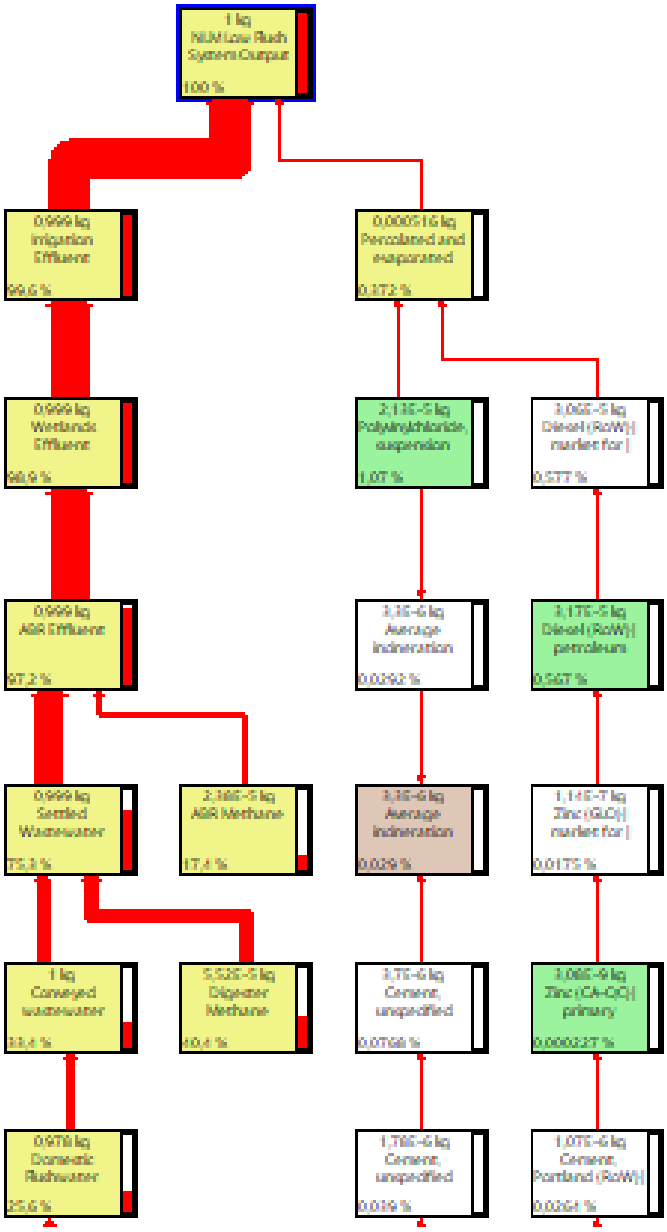

Figure I- 2: Process network diagram for System B illustrating Global warming contributions

Appendix I-3: Global Warming System C

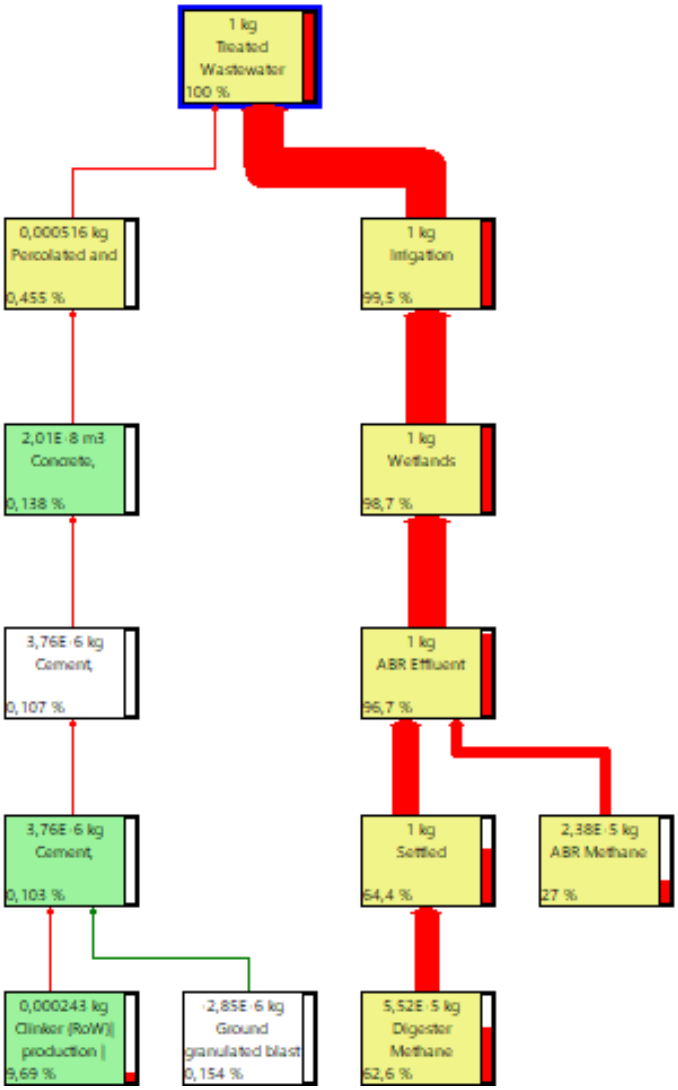

Figure I- 3: Process network diagram for System C illustrating Global warming contributions

Appendix J: Normalisation Factors for CML 2001 Methodology

Impact category	Name	Normalisation factor				
		the Netherlands, 1997	West Europe, 1995	World, 1995	World, 1990	Unit
acidification potential	average European	6.69E+8	2.74E+10	3.22E+11	3.24E+11	kg SO2-Eq/a
acidification potential	generic	7.93E+8	2.94E+10	3.35E+11	3.29E+11	kg SO2-Eq/a
climate change	GWP 100a	2.53E+11	4.82E+12	4.15E+13	4.41E+13	kg CO2-Eq/a
climate change	GWP 20a	2.96E+11	5.83E+12	5.40E+13	5.69E+13	kg CO2-Eq/a
climate change	GWP 500a	2.21E+11	4.04E+12	3.31E+13	3.36E+13	kg CO2-Eq/a
climate change	lower limit of net GWP	2.51E+11	4.49E+12	4.04E+13	4.02E+13	kg CO2-Eq/a
climate change	upper limit of net GWP	2.56E+11	4.93E+12	4.41E+13	4.61E+13	kg CO2-Eq/a
eutrophication potential	average European	1.35E+9	3.22E+10	3.90E+11	3.56E+11	kg NOx-Eq/a
eutrophication potential	generic	5.02E+8	1.25E+10	1.32E+11	1.33E+11	kg PO4-Eq/a
freshwater aquatic ecotoxicity	FAETP 100a	6.44E+9	4.72E+11	1.81E+12	1.81E+12	kg 1,4-DCB-Eq/a
freshwater aquatic ecotoxicity	FAETP 20a	6.33E+9	4.69E+11	1.79E+12	1.78E+12	kg 1,4-DCB-Eq/a
freshwater aquatic ecotoxicity	FAETP 500a	6.76E+9	4.82E+11	1.88E+12	1.89E+12	kg 1,4-DCB-Eq/a
freshwater aquatic ecotoxicity	FAETP infinite	7.54E+9	5.05E+11	2.04E+12	2.07E+12	kg 1,4-DCB-Eq/a
freshwater sediment ecotoxicity	FSETP 100a	7.45E+9	4.38E+11	1.89E+12	1.89E+12	kg 1,4-DCB-Eq/a
freshwater sediment ecotoxicity	FSETP 20a	7.18E+9	4.31E+11	1.84E+12	1.83E+12	kg 1,4-DCB-Eq/a
freshwater sediment ecotoxicity	FSETP 500a	8.27E+9	4.62E+11	2.07E+12	2.09E+12	kg 1,4-DCB-Eq/a
freshwater sediment ecotoxicity	FSETP infinite	1.02E+10	5.18E+11	2.46E+12	2.53E+12	kg 1,4-DCB-Eq/a
human toxicity	HTP 100a	1.87E+11	7.49E+12	5.67E+13	5.94E+13	kg 1,4-DCB-Eq/a
human toxicity	HTP 20a	1.86E+11	7.48E+12	5.67E+13	5.94E+13	kg 1,4-DCB-Eq/a
human toxicity	HTP 500a	1.87E+11	7.50E+12	5.68E+13	5.94E+13	kg 1,4-DCB-Eq/a
human toxicity	HTP infinite	1.88E+11	7.57E+12	5.71E+13	6.00E+13	kg 1,4-DCB-Eq/a
ionising radiation	ionising radiation	1.43E+2	4.86E+4	1.34E+5	1.12E+5	DALYs/a
land use	competition	3.04E+10	3.27E+12	1.24E+14	1.24E+14	m2a/a
malodours air	malodours air					m3 air/a
marine aquatic ecotoxicity	MAETP 100a	1.16E+10	4.64E+11	1.90E+12	2.94E+12	kg 1,4-DCB-Eq/a
marine aquatic ecotoxicity	MAETP 20a	2.74E+9	1.16E+11	4.83E+11	6.59E+11	kg 1,4-DCB-Eq/a
marine aquatic ecotoxicity	MAETP 500a	6.01E+10	2.33E+12	9.83E+12	1.55E+13	kg 1,4-DCB-Eq/a
marine aquatic ecotoxicity	MAETP infinite	3.18E+12	1.14E+14	5.12E+14	7.55E+14	kg 1,4-DCB-Eq/a
marine sediment ecotoxicity	MSETP 100a	1.37E+10	5.90E+11	2.40E+12	3.56E+12	kg 1,4-DCB-Eq/a
marine sediment ecotoxicity	MSETP 20a	4.54E+9	2.17E+11	8.91E+11	1.14E+12	kg 1,4-DCB-Eq/a
marine sediment ecotoxicity	MSETP 500a	6.01E+10	2.38E+12	1.00E+13	1.57E+13	kg 1,4-DCB-Eq/a
marine sediment ecotoxicity	MSETP infinite	2.99E+12	1.04E+14	4.69E+14	6.79E+14	kg 1,4-DCB-Eq/a
photochemical oxidation (summer smog)	EBIR					kg formed ozone/a
photochemical oxidation (summer smog)	high NOx POCP	1.82E+8	8.24E+9	9.59E+10	1.04E+11	kg ethylene-Eq/a
photochemical oxidation (summer smog)	low NOx POCP	1.57E+8	6.31E+9	8.69E+10	9.19E+10	kg ethylene-Eq/a
photochemical oxidation (summer smog)	MIR					kg formed ozone/a
photochemical oxidation (summer smog)	MOIR					kg formed ozone/a
resources	depletion of abiotic resources	1.71E+9	1.48E+10	1.57E+11	1.58E+11	kg antimony-Eq/a
stratospheric ozone depletion	ODP 10a	1.17E+6	1.87E+8	8.99E+8	1.64E+9	kg CFC-11-Eq/a
stratospheric ozone depletion	ODP 15a	1.08E+6	1.46E+8	6.93E+8	1.32E+9	kg CFC-11-Eq/a
stratospheric ozone depletion	ODP 20a	1.02E+6	1.26E+8	6.01E+8	1.17E+9	kg CFC-11-Eq/a
stratospheric ozone depletion	ODP 25a	9.87E+5	1.14E+8	5.43E+8	1.07E+9	kg CFC-11-Eq/a
stratospheric ozone depletion	ODP 30a	9.57E+5	1.05E+8	5.01E+8	1.00E+9	kg CFC-11-Eq/a
stratospheric ozone depletion	ODP 40a	9.21E+5	9.54E+7	4.50E+8	9.23E+8	kg CFC-11-Eq/a
stratospheric ozone depletion	ODP 5a	1.38E+6	3.11E+8	1.61E+9	2.59E+9	kg CFC-11-Eq/a
stratospheric ozone depletion	ODP steady state	9.77E+5	8.30E+7	5.15E+8	1.14E+9	kg CFC-11-Eq/a
terrestrial ecotoxicity	TAETP 100a	1.72E+8	2.03E+10	1.40E+11	1.48E+11	kg 1,4-DCB-Eq/a
terrestrial ecotoxicity	TAETP 20a	1.50E+8	1.92E+10	1.35E+11	1.41E+11	kg 1,4-DCB-Eq/a
terrestrial ecotoxicity	TAETP 500a	2.61E+8	2.44E+10	1.61E+11	1.78E+11	kg 1,4-DCB-Eq/a
terrestrial ecotoxicity	TAETP infinite	9.20E+8	4.73E+10	2.69E+11	2.64E+11	kg 1,4-DCB-Eq/a

Figure J-1: Normalisation factors for CML 2001 methodology (Guinee, 2002)

Table J-1: Normalisation factors used for this study

Impact Category	Name	World 1995
Marine Aquatic Ecotoxicity	MAETP infinite	5.12E+14
Human toxicity	HTP infinite	5.71E+13
Climate Change	GWP 100a	4.15E+13
Freshwater Aquatic Ecotoxicity	FAETP infinite	2.04E+12
Acidification Potential	generic	3.35E+11
Terrestrial ecotoxicity	TAETP infinite	2.69E+11
Resources	depletion of abiotic resources	1.57E+11
Eutrophication Potential	generic	1.32E+11
Photochemical oxidation (summer smog)	high Nox PCOP	9.59E+10
stratospheric ozone depletion	ODP 5a	1.61E+09