DECISION SUPPORT TOOL FOR ASSESSING THE SUSTAINABILITY OF WATER REUSE FOR POTABLE APPLICATIONS IN SOUTH AFRICAN COMMUNITIES

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DECLARATION

I declare that this thesis is my own unaided work. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

(Signature of candidate)

...................day of 2018

ABSTRACT

In South Africa (SA), freshwater scarcity can significantly be abated by the reuse of treated municipal wastewater for potable applications. However, the question of what a sustainable water reuse scheme is, and how the sustainability of the scheme can be assessed need to be answered. This is imperative to the overall success of water reuse schemes and the movement towards contributing to a low carbon, sustainable society. To achieve this goal, there is need to develop a decision support tool that would enable a balance between the institutional, social, economic, technical and environmental attributes involved in the sustainability of water reuse for potable applications. The aim of this research work is to develop an integrated sustainability index (ISI) as a Decision Support System (DSS) for assessing the sustainability of water reuse for potable applications in South African communities.

To address the issue of how much water is available for reuse; this study developed a linear regression model and a Bayesian Network model for predicting usable return flow (i.e. wastewater that can be treated and used for other beneficial purposes) from agricultural and domestic activities in SA water management areas. The result of the study shows that about 8% of the agricultural water use is potentially reusable while about 34% of the total domestic water use is potentially reusable. Furthermore, the study also shows that given the agricultural water use, the usable return flow from agricultural activities can be predicted with a reasonable accuracy as well as given the domestic water use and the population density; the usable return flow from domestic activities can be predicted with a reasonable accuracy.

A study was carried out for development and selection of criteria for the sustainability assessment process based on their relevance and degree of importance to the sustainability assessment process by consulting with 51 experts in SA water sector with knowledge on reuse. The preliminary group of criteria comprises of 22 primary criteria and 53 secondary criteria which were reduced and harmonized to 16 primary criteria and 27 secondary criteria based on experts' opinion. These criteria constitute the quantitative and qualitative sustainability assessment criteria modules of the ISI. The

quantitative modules consist of economic, technical and environmental assessment criteria while qualitative modules consist of social and institutional assessment criteria. The quantitative module begins with an estimation of water saving potentials for the selected case study sites namely Emalahleni, Hendrina and Beaufort West municipalities. The result of the water saving potential analysis indicates that water demand for domestic activities can be reduced by approximately 22.8 %, 47.3% and 29.3% in Emalahleni, Hendrina and Beaufort West municipalities respectively. With the challenges due to data availability, this module provides a quantifiable factor to illustrate potable water savings due to reuse as a justification for reuse project. For assessing energy intensity and operation and maintenance costs which are classified as quantitative environmental and economic criteria respectively, two models were developed: (i) an activity based energy utilization (ABEU) model for assessing the energy intensity of water reuse systems and (ii) an integrated cost analysis model for evaluating operational and maintenance costs of water reuse systems. The two models were applied to two water reclamation plants in Mpumalanga province, South Africa. The result of ABEU indicated that the overall energy utilized by plant A and B are 4.53kWh/m^3 and 2.1803kWh/m^3 for the production of an average volume of 19,295 m^3 and 14,236 m^3 of reclaimed water for potable application respectively. The result of the integrated cost analysis model indicated that overall operation and maintenance cost of production of reclaimed water for plant A and plant B respectively are 16.1 ZAR/m^3 and 11.4 ZAR/m^3 respectively. The social qualitative module of the ISI contains simplified questionnaire that was developed to evaluate social dimension of sustainability.

A hypothesized behavioral model was developed to investigate factors influencing intention to accept recycled/reclaimed water for potable applications. The results obtained from the application of the hypothesized model to Emalahleni and Hendrina municipalities show that factors such as knowledge of benefits of reuse, ethical awareness (subjective norms), credibility of water service authority, and risk perception were vital to intention to accept reuse for potable applications.

The application the ISI to Emalahleni, Hendrina and Beaufort West municipalities showed the tool to be a robust tool and provide a good assessment of both qualitative and quantitative criteria in the assessment of water reuse for potable applications. Beaufort West municipality has the highest score of 0.7484, followed by Hendrina municipality with a score of 0.7182 and Emalahleni municipality with the lowest score of 0.5891. The result of the individual sustainability dimension analysis shows that Beaufort West has the highest scores of 0.9179 and 0.8473 in social and institutional dimensions respectively in comparison with Hendrian and Emalahleni.

It can be deduced from the scores of the sustainability dimensions that economic dimension fares the worst with an average score of 0.4756 across the of the three case study sites. Hence, it appears that economic criteria contribute to challenges impeding the transition towards a sustainable state. A satisfactory score of 0.9190 in social dimension analysis was recorded for Hendrina as well with a moderate score of 0.6350 recorded for Emalahleni. Hence, in Emalahleni resources must be allocated to educate the public on reuse. Further analysis indicates that the relative strength of the three case study sites lies in the technical dimension, with score of 0.7756, 0.8409 and 0.8310 for Emalahleni, Hendrina, and Beaufort West respectively. On the other hand, economic dimension contributes the least to the overall scores of the case study sites, with scores as low as 0.3877, 0.5643and 0.4778 in Emalahleni, Hendrina and Beaufort West respectively. Based on the classification of the range of ISI scores and the corresponding interpretation, Emalahleni municipality falls into the category of "low potential for sustainability" at the period the assessment. On the other hand, Hendrina and Beaufort West municipalities falls under the category of "reasonable potential for sustainability" at the period the assessment was carried out.

DEDICATION

This project work is dedicated to THE ALMIGHTY GOD, the creator of all things and our LORD JESUS CHRIST, for HIS marvelous grace and mercy for the gift of life and for sparing my life up to this moment.

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The opportunity to be especially grateful to people and circumstances that influence and moderate our lives is rarely common. Therefore the opportunity to do that here is considered a privilege. I would like to appreciate most especially, the wonderful love of my father, Prof. Alade Abimbade and my mother; the quintessence of motherhood, Mrs. Kafilat Ayoola Abimbade , for the unparalleled sacrifice of their comfort and ego in a bid to provide sound and quality education for my siblings and I.

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LIST OF PUBLICATIONS

Journal Articles

Abimbade A.A. and Ilemobade, A.A. Acceptability of Recycled/Reclaimed Water for Potable Uses amongst Domestic Respondents: Testing a Socio-Psychological Model. *Under preparation*

Abimbade A.A. and Ilemobade A.A. Application of an Integrated Sustainability Index as a Multi-Criteria Decision Support Tool for Assessing Water Reuse Sustainability in South African comunities. *Under preparation*

Abimbade A.A. and Ilemobade A.A. An Activity Based Energy Consumption Model for assessing Energy intensity of Water Reuse System for Direct Potable Reuse. *Under preparation*

Mamane, S., **Abimbade, A.A**. and Ilemobade, A. Prediction of Water Reuse Potential in South African Water Management Areas *(Submitted for publication)*

Conferences

Abimbade, A.A., Ilemobade, A.A., (2015). Development of Criteria for Assessing Sustainability Performance of Urban Water Reuse Schemes for Potable Applications in South African Communities" presented at the *Water Institute of Southern Africa (WISA)* Water Reuse Symposium, September 2015.

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Abimbade A.A., Ilemobade A.A., (2018). Energy Consumption Model for Operation and Maintenance Phase of Water Reuse Systems for Potable Applications *Water Institute of Southern Africa (WISA)* WISA 2018 conference *(Abstract accepted)*

LIST OF SYMBOLS AND ABBREVIATION

%NRW	Percentage of Non-Revenue Water
ABC	Activity-Based Costing
ABEU	Activity-Based Energy Utilization
AFFI	Adjusted Goodness of Fit
AHP	Analytical hierarchy process
ASCE	American Society of Civil Engineers
ATW	Advanced Treated Water
AUWSs	Alternative Urban Water Systems
AWTF	Advanced Water Treatment Facility
AWU	Agricultural water use
AwwaRF	Awwa Research Foundation
BN	Bayesian Network
CD	Capacity Development
CDW	Cost of Domestic Water
CFI	Comparative Fit Index
CIW	Cost of Irrigation Water
CP	Compromise programming
CPD	Conditional Probability Distributions
CPT	Conditional Probability Table
CPWC	Cooperative Programme on Water and Climate
CRF	Capital Recovery Factor
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organization
CUWSs	Conventional Urban Water Systems
DAG	Directed Acyclic Graph
DEAT	Department of Environment Affairs and Tourism
DFPSIR	Driving Forces-Pressure-State-Impact-Response
DPR	Direct Potable Reuse
DPSEEA	Driving Forces-Pressure-State-Exposure-Effect-Action

DSS	Decision Support System
DWA	Department of Water Affairs
DWTP	Drinking Water Treatment Plant
DWU	Domestic Water Use
EA	Exergy analysis
EEA	European Environment Agency
EIA	Environmental Impact Assessment
ELECTRE	Elimination and choice expecting reality
ESB	Engineered Storage Buffer
EU	European Union
FT	Percentage of Flushed Toilet connected to Sewerage
GEC	Global Environment Centre Foundation
GHG	Green-House gas
GP	Goal programming
GUI	Graphic User Interface
IPR	Indirect Potable Reuse
IRIS	Integrated Regulatory Information System
IRP	Integrated Resources Planning
ISI	Integrated Sustainability Index
IWRM	Integrated Water Resources Management
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MADMs	Multi-Attribute Decision-Making Methods
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Aiding
MCDM	Multi-Criteria Decision Making
MDGs	Millennium Development Goals
MDH	Minnesota Department of Health
MF	Micro-filtration
MFA	Material Flow Analysis

MIP	Mixed Integer Programming
MODMs	Multi-Objective Decision-Making Methods
MoM	Method of Measurement
MRA	Microbial Risk Assessment
NAIADE	Novel approach to imprecise assessment and decision environments
NFI	Normalized Fit Index
NNFI	Non-normalized Fit Index
NWRS	National Water Resource Strategy
O&M	Operation and Maintenance
OECD	Organization for Economic Co-operation and Development
PD	Population Density
pH	Power of hydrogen
PSR	Pressure-State-Response
RDP	Reconstruction and Development Program
RFI	Relative Fit Index
RMSEA	Root Mean Square Error of Approximation
RO	Reverse Osmosis
SA	South Africa
SAT	Soil Aquifer Treatment
SAWS	South Africa Weather Services
SD	Sustainable development
SEA	Strategic Environmental Assessment
SEM	Structural Equation Modeling
SPI	Standard Precipitation Index
SPSS	Statistical Package for Social Sciences
SS	Special Ordered Set
SUWM	Sustainable Urban Water Management
SUWSs	Sustainable Urban Water Systems
SWARD	Sustainable Water industry Asset Resource Decisions
SWITCH	Sustainable Water Management Improves Tomorrow's Cities Health

TBL	Triple Bottom Line
TOPSIS	Technique for order of preference by similarity to ideal situation
UF	Ultrafiltration
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNCSD	United Nations Commission on Sustainable Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
URFA	Usable Return Flow from Agricultural Activities
URFU	Usable Return Flow from Urban Activities
USEPA	United States Environmental Protection Agency
UWM	Urban Water Management
UWP	Urban Water Programme
UWRM	Urban Water Resource Management
UWSs	Urban Water Systems
UWSS	Urban Water Self-Sufficiency
WCED	World Commission report on Environment and Development
WHO	World Health Organization
WISA	Water Institute of Southern Africa
WMAs	Water Management Areas
WRC	Water Research Commission
WRI	Wastewater Reuse Index
WRP	Water Reclamation Plant
WRSs	Water Reuse Systems
WSA	Water Service Authority
WSI	Water Stress Index
WSNIS	Water Services National Information System
WSUD	Water-Sensitive Urban Design
WTP	Water Treatment Plant

WU	Water Use
WUPI	Water Utility Performance Index
WVPP	Water Volume per person per day

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CHAPTER 1

1 INTRODUCTION AND BACKGROUND TO THE STUDY

1.1 Introduction

Freshwater is a renewable resource. However, its availability for anthropogenic use and other purposes is increasingly limited contrary to common perceptions that water is an infinite resource. Increasing water demand as a result of population growth¸ increasing urbanization, economic growth and inefficient infrastructure is challenging the limits of conventional water resources availability (Rygard et al. 2011). It is imperative therefore that water, as a depleting resource is managed and developed in a sustainable and integrated manner to effectively and efficiently address the challenges associated with its availability and utilization. Water service providers are increasingly turning to new technologies and strategies that will enable cities to become self –reliant on the available water resources. South Africa (SA) is a water scarce country and the high variability in rainfall distribution often results in excess water volumes in some areas and insufficient in others (Adewumi et al. 2011). Water availability and demand patterns across SA differs considerably between catchments thus asserting the need for better understanding and management of water resources with active participation from all stakeholders. The spatial and temporal variation of water availability within the country is significant in provinces like Gauteng, the most economically productive province of the country which imports a substantial proportion of its freshwater to meet demand (Kotze, 2011).

According to Ilemobade et al. (2012), "water reuse has the potential to supplement freshwater resources, provide reliable water services in remote or environmentally sensitive locations, mitigate the rising costs of meeting drinking water treatment and wastewater discharge standards, and reduce sewage discharges to water bodies". Globally, there is increased interest in water reuse and particularly in South Africa (SA), because of its potential to supplement scarce freshwater resources in the face of increased demand and aridity (Ilemobade et al. 2012). With the increasing knowledge about and understanding of the potential and advantages of water reuse, water reuse projects for potable applications schemes have been successfully implemented in some developed and developing countries (Leverenz et al. 2011). According to Rodriguez et al. (2009), it is technically possible and economically affordable to produce potable water quality from recycled water, and this has led to the broader application of water reuse for indirect and direct potable uses. With the broadened application of reclaimed and recycled water, sustainability of water reuse projects is paramount to cater for water reuse project expansion and new end-user exploration. Although water reuse is generally perceived as an established approach to resource efficiency, its interaction with the wider environment (e.g., energy implications, scale-dependent failure risk, and associated consequences) and trade-offs between decision influencing parameters and long-term sustainability, lack a systematic and integrated analysis (Ilemobade 2012; Chen et al. 2013). In order to proceed towards achieving the goals of sustainable development and sustainable urban water management (UWM), a critical assessment of reuse decision influencing parameters must be carried out through the development and application of tools to improve understanding and address the current knowledge gaps and the short, medium and long-term interventions that are required to give momentum to planning, progressive implementation and sustainability of direct and indirect water reuse projects for domestic use in South African communities.

1.2 Problem Statement

A society's ability to develop and prosper can be linked directly to the development, utilization and protection of its available water resources. A major conclusion derived from the 1991 Dublin conference on water resources was that "since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of the natural ecosystem" (Dublin statement 1992). The Dublin Conference in 1991 was a precursor to the 1992 United Nations Rio de Janeiro Earth Summit (UNCED) that further buttressed the conclusion of the 1991 conference. The key to achieving the overall goal of sustainable development is embedded in the sustainable use and holistic management of freshwater resources (DEAT 1998; MDH 2000; UNESCO 2003). Water reuse systems, as part of physical infrastructure (i.e. facilities required to meet basic needs such as water supply, sanitation, basic transportation and housing) cannot be delineated from sustainable development of a society's water resources management. To further complicate the challenges facing existing freshwater resources, pollution caused by discharge of growing volumes of wastewater into receiving water bodies is on the rise making freshwater a limited resource. According to a United Nations World Water Development Report (2006), 'providing the water needed to feed a growing population and balancing this with all the other demands on water, is one of the great challenges of this century'. Therefore, water scientists and policy makers are faced with the task of efficiently allocating scarce resources and finding additional/alternative sources of supply to address the perceived growing demands (Keremane and McKay, 2007). According to Keremane and McKay (2007), actions to counter this challenge should be sustainable without depleting natural resources or harming the environment. Hence, Keremane and McKay suggested two actions to address water scarcity challenges: (i) re-allocating available supplies through water marketing strategies (Dinar et al. 1997; Easter et al. 1999; Bjornlund 2003) and (ii) source substitution (Hespanhol 1997; Cullen 2004). According to Simpson (1994), water marketing strategies can create an avenue for efficient allocation of scarce resources and improvement of water use efficiency. Hespanhol, (1997), suggests that source substitution is the most appropriate alternative to satisfy less restrictive uses, thus allowing water that meets the required quality to be used for domestic purposes. This study deals with the latter option, which is argumentation of fresh water supplies through source substitution.

Water reclamation and recycling are considered as key components of water and wastewater management policies in the event of water scarcity. Reclaimed water is now considered by some as a reliable water source to augment limited freshwater resources, without jeopardizing the health of the public and the environment (Asano 2001; Bahri 2001; Angelakis et al. cited in Abu Madi et al. 2003; Murni et al. 2004). Water reuse involves processing and utilization of partially or fully treated wastewater effluent from a variety of sources (e.g. domestic, industrial and mining activities) for a beneficial application such as drinking purposes, groundwater recharge, reservoir augmentation, industrial use or irrigation. Wastewater can be treated to a high level of purity with available treatment technology and placed in an engineered storage/environmental buffer to augment imported water, recharge groundwater aquifers, irrigate agriculture and landscapes, fight fires and provide recreation. Although, due to several issues associated with wastewater usage and application, implementing sustainable water reuse schemes have raised some concerns in the past. According to Keremane and McKay (2007), some of the major challenges facing successful development of water reuse schemes are: (i) conflicting agendas among multiple water provision agencies; (ii) addressing water rights issues; (iii) dealing with opponents to recycling/reuse; (iv) modifying existing regulations; and (v) acquisition of funds (Kasower 1998; Ritchie et al. 1998; Mills 2000; Asano 2001; all cited in Haddad 2002; Murni et al. 2004). However, according to Dimitriadis (2005), some successful and well planned reuse schemes have contributed to sustainability. Some examples of such are potable reuse initiatives which involve the reuse of extensively treated wastewater for drinking purposes have been successfully implemented in Windhoek-Namibia, Beaufort West-South Africa, Big Springs-Texas-U.S. and Singapore. Adewumi et al. (2010) presented an overview and quantitative analysis of the SA water resources situation in order to put the need for wastewater reuse into perspective. The study highlighted some valuable experiences of wastewater reuse in SA and also presented a strong argument for the broader implementation of water reuse initiatives in many arid SA communities. The study also reported a usable return flow (i.e. treated wastewater) which comprises about 14% of the total wastewater generated. This brings into focus the unexploited potential of the direct reuse of these substantial return flows for non-potable applications and was a reflection of the level of infancy of wastewater reuse in SA.

In SA, there is a growing paradigm shift towards reuse for potable applications as evident in the Water Research Commission report by Niekerk and Schneider (2013) on implementation plan for direct and indirect water reuse for domestic purposes. Furthermore, Leverenz et al. (2011) highlighted the following factors that favor reuse for potable applications (especially direct potable reuse) over non-potable applications:

- The significant cost of associated with non-potable water reuse in urban areas for providing separate reticulation and storage systems for reclaimed water. This problem can easily be solved by implementing direct potable reuse which can utilize the existing water distribution system for conveyance of reclaimed water.
- Potable reuse offers the opportunity to significantly reduce the distance that reclaimed water would need to be transported and significantly reduce the head against which it must be pumped; thereby reducing costs.
- Direct potable reuse has the potential to allow for full reuse of available reclaimed water in metropolitan areas, using the existing water reticulation infrastructure.
- An important element of a direct potable reuse system is the ability to provide water of a specified quality reliably all the time. Hence, reclaimed water is a potential reliable source of supply which exists in close proximity to the demand.

The ever increasing interest in reuse and the multiplicity of complex issues involved have led to quite a number of publications over the last 2 decades. These publications addressed different aspects of water reuse such as treatment train and technologies, perceptions of beneficiaries, and water-energy interactions (e.g. Po et al., 2005; Hurlimann and McKay, 2007; Adewumi et al 2010; Alves et al., 2011, Ward et al., 2012; Ilemobade et al., 2012, and Chen et al., 2013). These studies have been valuable in documenting water reuse potential, concepts and experiences in both developed and developing communities. The studies have been mostly limited in incorporating the diverse interdisciplinary and multidisciplinary water reuse criteria (e.g. social, environmental, technical, economic and institutional) into a composite indicator/barometer that will enhance a holistic and deeper understanding of water reuse, thereby, permitting a systematic and integrated analysis of reuse, the decisions influencing parameters in the wider environment and long term sustainability. Moreover, in the context of water reuse schemes as part of sustainable development; there has been little investigation of benchmarking “good sustainability practice” due to limited water reuse applications and wider-user uptake in developed and developing communities. Benchmarking analysis and techniques has become a strategic tool employed by water regulators across the globe for monitoring and measuring performance of water utilities (De Witte and Marques, 2012; and Gallego-Ayala et al. 2014). It has been claimed that benchmarking systems lack an articulated theoretical and contextual definition of sustainability and a clear epistemological link between the definition and indicators (Davidson, 2010). This is especially relevant in a developing country such as SA where a context-specific interpretation of sustainability needs to take into account social and institutional issues such as poverty alleviation, strengthening democracy, skills levels, and biodiversity conservation (Carden, 2013).

With increased water reuse for diverse applications over the last 2 decades, there is need for a holistic indicator which does not currently exist to measure water reuse sustainability performance (Ilemobade 2012). The novel indicator development process is envisaged to include extensive data collection from literature and through case studies, expert opinions, and the identification and quantification of impacts of different reuse criteria (through the use of modeling and available simulation tools). It will also involve the development of a set of matrices to evaluate water reuse sustainability for a range of contexts and scales. An indicator such as this, will be invaluable in a number of ways including – (i) providing a platform to model the impact of different water reuse criteria; (ii) assessing the sustainability of water reuse initiatives; (iii) as an input into the futuristic scenario planning of urban environments such as was undertaken by Boyko et al., (2012), (iv) creating an aggregated sustainability assessment index for criterion/set of criteria that permeate across the diverse and multiple decision influencing parameters associated with reuse would simplify sustainability assessment process and allow better comparison between different water reuse initiatives as advocated by Listowski et al., (2009). The indicator will assist decision making for context specific wider uptake of water reuse options in developing communities, thereby encouraging resource efficiency, support water security initiatives, help to minimize risks and negative environmental implications (e.g. energy and associated greenhouse gas emissions).

This study therefore attempts to: (i) develop a generic and dynamic model for futuristic scenario analysis of wastewater reuse potential for wider uptake in SA; (ii) develop an integrated sustainability index (ISI) for assessing water reuse , thereby, enhancing comparative assessment of different potable reuse applications in SA; (iii) validate the generic ISI which will incorporate reliability, resilience and vulnerability measures for various inter- and multi-disciplinary water reuse sustainability criteria/aspects. According to Dahl (2012) "*even at the national level, present indicators address what might be called the "hardware" of national sustainability in the measurable status of and trends in environmental, social and economic parameters (pollution levels, poverty, education, technology, energy resource consumption, etc) rather than the processes of decision making and control (the "software") that determine whether sustainability is really taken in account in decision making*". Simply compiling many separate indicators of sustainability cannot provide an adequate measure of overall sustainability of a system. Modeling system dynamics, exploring resilience and tipping points, and developing alternative scenarios, can help anticipate vulnerabilities in the natural, social and economic system. Adding indicators of processes and dynamic change would help to discriminate between conscious progress towards a sustainable system and incidental improvements or correlations that result, perhaps, from rising levels of economic prosperity (Dahl 2012).

1.3 Research Aim and Objectives

It is evident from the discussion in the previous sections that water reuse for potable applications is a viable and sustainable alternative water management strategy to tackle and alleviate the challenges facing water supply security in water scarce regions across the globe. In the light of this, there is need to develop tools that will assist decision making when assessing critical factors governing water reuse sustainability.

The primary aim of this research is to develop a decision support system (DSS) for assessing the sustainability of water reuse for potable applications in SA communities. The tool includes an integrated sustainability index (ISI) that will assist decision makers and relevant stakeholders in the water industry to assess a balance amongst sustainability attributes (i.e. social, economic, environmental, technical and institutional) when assessing water reuse sustainability. In this way, a more balanced view is attained of the pertinent factors that influence the sustainability of urban water reuse for potable applications. Moreover, the tool can serve as an indicator to holistically understand and benchmark water reuse systems for potable applications, thereby, assisting in decision making for context-specific, wider uptake and comparative assessment of potable water reuse options in SA. The aim of this research will be achieved through the following specific objectives:

1. To critically review integrated water resources reuse concepts, practice, tools, technologies and management;
2. To estimate water reuse potential in South African water management areas
3. From (1), to identify, develop and/or select critical criteria that permeate sustainability attributes and that influence the sustainability of water reuse for potable applications
4. To develop/adapt a framework for proposed Integrated Sustainability Index for assessing water reuse for domestic potable applications in SA communities;
5. To determine/develop/adapt models that will quantify the impact of criteria on water reuse;
6. To calibrate and validate the models in (5) using data from literature and selected case studies;
7. To measure water reuse sustainability performance in selected South African communities using the ISI for different water reuse options.

1.4 The relevance of this study

The introduction of sustainable development in the World Commission report on Environment and Development (WCED, 1987) has resulted in a paradigm shift in development. The widely used definition of sustainable development proposed by the Brundtland Commission (1987) states that: "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". The necessity to redefine sustainable development arose from the increased depletion of natural resources, energy consumption and ecosystem pollution in the twenty-first century (Motevallian and Tabesh, 2011). To this end, treated wastewater is now considered a new and reliable water source to supplement limited freshwater resources, without compromising public health (Ogoshi et al., 2001; Bahri 2001cited in Madi et al., 2003; Po et al., 2004 cited in Keremane and McKay, 2007). As part of the national water resources strategy, water reuse has been identified as one of the important strategies to balance water availability with water requirements in the future and the extent of water reuse in SA is very likely to increase substantially over time (NWRS, 2011). In SA, the reuse of water accounts for approximately 14 % of total water use and return flows account for a large part of water available for use from some of the important river systems (Niekerk and Schneider, 2013). There is need for monitoring and information tools to assess the quantity, quality, use and sustainability aspects of water reuse at catchment and national levels, as well as compliance with resource quality objectives, health of aquatic ecosystems and atmospheric conditions. This is recognized in the National Water Act (No. 36 of 1998), which states that the Minister is required to establish a national monitoring and information system for water resources as soon as possible. The aims of the system are provided in Section 140 of the Act as:

a. *To store and provide data and information for the protection, sustainable use and management of water resources;*
b. *To provide information for the development and implementation of the national water resource strategy;*
c. *To provide information to water management institutions, water users and the public –*
    i. *For research and development;*
    ii. *For planning and environment impact assessments;*
    iii. *For public safety and disaster management; and*
    iv. *On the status of water resources.*

One method of fulfilling some of these requirements is through the development and use of suitable sustainable development indicators that provide a means of communicating information about progress towards a goal (such as sustainable water resource management) in a significant and simplified manner. In this research, a decision support system for assessing the sustainability of water reuse for potable applications in South African communities was developed to assist relevant stakeholders (administration, service providers, engineering companies, water management bodies, etc.) involved in the development and implementation of water reuse initiatives as an alternative water management strategy.

A comprehensive assessment exercise to examine the interdisciplinary and multidisciplinary parameters such as technical (e.g. operational efficiency), economic (e.g. whole life cycle costs), environmental (including public health and safety), social (public acceptance) and institutional (structure and characteristics) issues associated with water reuse was addressed in this study. These factors contribute to the decisions that are pertinent to the sustainability of reuse projects for potable applications over time. The due consideration of these factors would significantly contribute to positive decisions and if need be may contribute to the re-evaluation of decisions and policies related to reuse. Accordingly, within the scope of this research work, the different aspect of each sustainability attribute is addressed. Questions such as what a sustainable water reuse scheme is and how the sustainability of a reuse scheme can be assessed will be answered. The ISI will be developed so that it can be used as a baseline tool by water and wastewater plant operators, water boards and water services providers to evaluate the sustainability of existing schemes. It is also hoped that it would be valuable as a guideline for designing and developing water reuse schemes in SA communities where water reuse schemes are being contemplated. More importantly, it is hoped that the ISI will be valuable as a tool for certification of water reuse schemes in SA.

1.5 Layout of Dissertation

This thesis contains 9 chapters including this introductory chapter, eight appendices and a comprehensive list of reference. Figure 1.1 depicts the flow chart of the layout of the report.

Chapter 1 contains the introduction, background to the study, motivation and problem statement, research aim and objectives, as well as the need for/relevancy of the study.

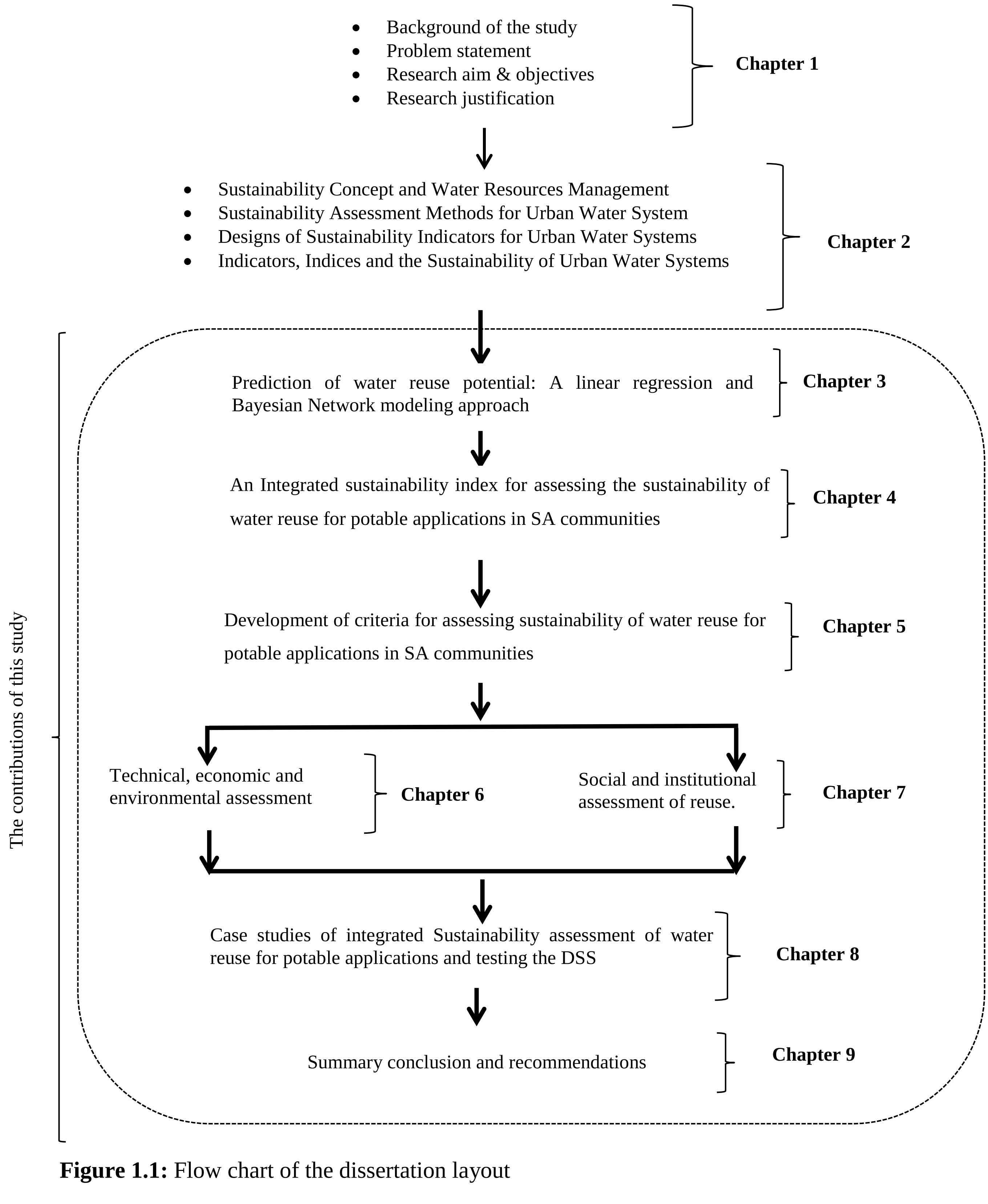


Figure 1.1: Flow chart of the dissertation layout

The second chapter reviews literature on various aspects pertaining to sustainable urban water management, the theory and methods of sustainability assessment, and a contextual description of water reuse for potable application as an alternative strategy for urban water management in South Africa.

Chapter three describes the development and application of linear regression and Bayesian Network modeling approach for estimating potential usable return flows from the agricultural and urban sectors that may be reused in South African's water management areas.

Chapter four provides specific detail on the development of the ISI for assessing water reuse for domestic potable applications. This chapter presents the theoretical framework that was adopted for the sustainability assessment process.

Chapter five describes the development of the criteria that are the building blocks of the ISI. The data identified for the computation of the ISI, as well as some detail on the aggregation and weighting methods that were employed.

Chapter six focuses on the technical, economic and environmental assessment framework within the DSS. The technical, environmental and economic assessment focuses on the treatment unit processes of the reuse scheme for potable applications.

The methodology used in the development of the treatment train is highlighted. Information contained in the knowledge base for each unit process and their technical and economic quantitative criteria (i.e. whole life cycle costs, resource utilization intensity, waste generation and management etc.) and qualitative criteria (i.e. habitat/wetland restoration/conservation and management plan for controlling disease vectors) are described. This chapter also describes the procedure and rules employed in the DSS for the selection of treatment train processes. Furthermore, this chapter describes (i) a mass balance approach for evaluating water saving potential due to reuse, (ii) the development and application of activity-based energy utilization (ABEU) model and an integrated cost analysis model (activity-based cost (ABC) and mathematical programming approaches) for assessing operation and maintenance cost of water reuse systems.

Chapter seven describes the methodology employed in the social (i.e. public perception) and institutional assessment. Factors that influence domestic respondent's acceptability of reclaimed/recycled water for potable applications are modeled and institutional capability and characteristics are incorporated into the DSS.

Chapter eight contains the testing of the DSS. This chapter discusses the results of the technical, economic, environmental, social and institutional assessment and the normalization, weighting and aggregation of the criteria employed. This chapter also discusses and summarizes ion of the overall findings of the research.

Chapters 1-8 (with the exception of chapter 3) provides discussion on the meaning of sustainability in the context of water reuse for potable applications as an alternative strategy in a developing country, as well as an indication of the likely impact of the use of an index such as the ISI at local and national government levels in SA. Some general comments on sustainability assessment in the context of water reuse initiatives for potable application in SA are given in Chapter 9, which also provides recommendations on future research in this field. The various Appendices provide supporting documentation for the main thesis including, data for the index calculation, and the comprehensive results from the application of the ISI to the three case study cities.

CHAPTER 2

2 URBAN WATER RESOURCES MANAGEMENT STRATEGIES, SUSTAINABLE DEVELOPMENT, AND SUSTAINABILITY METRICS (INDICATORS & INDEXES)

2.1 Introduction

The concept of sustainability has resulted in a paradigm shift in discussions around development policies and strategies at all tiers of government, institutions and organizations. The area of specific interest to hydrologists and water experts is the development and implementation of urban water systems (UWSs) to meet sustainability requirements and how to evaluate the performance of UWSs in attaining the objectives of sustainable development. This chapter focuses on sustainable UWSs, reviews the existing urban water management (UWM) practices and addresses the major impediments that exist on the pathway towards sustainable UWSs. The complexities involved in coordinating and collaborating diverse and multiple disciplines and the entities that manage drinking water, wastewater, and storm-water have made the management of UWSs a difficult task. As the world's population is increasingly more urbanised, comprehensive planning and management of life sustaining resources (such as water) is needed to support the continued flora and fauna existence in these urban centres. The quest for sustainable development and sustainability also motivated water researchers and experts to explore a new area of study in the context of UWM described as "sustainable urban water management (SUWM)".

The goal of SUWM is to encourage the use of scientific knowledge, practices and technologies to provide adequate water and sanitation to current users as well a/preservation of limited resources for the future generations with minimal damage to life sustaining ecosystems (Motevallian and Tabesh, 2011). Hence, UWSs that meet these requirements that characterise sustainability can be referred to as "sustainable urban water systems" (SUWSs). This chapter provides information on the rudimentary concepts of SUWM and SUWSs. To achieve this objective, firstly, different constituents of UWSs are reviewed. Secondly, the different views of the concept of sustainable development and sustainability, as well as, the objectives of SUWSs are discussed. Subsequently, an overview of the conventional methods employed to evaluate UWSs sustainability including sustainability indicators (SIs) and assessment techniques are presented. Lastly, specific practices across the globe and challenges of implementing SUWM are discussed.

2.2 Urban Water Management

UWSs are pivotal in ensuring that the well-being and health of communities are sustained and not compromised. UWSs comprise of water supply systems, wastewater collection and treatment systems and urban drainage systems (Motevallian and Tabesh, 2011). Water supply schemes involve the abstraction of water from raw water sources such as surface water bodies and the conveyance of the water to water treatment plants where it is treated to meet potable water requirements. Wastewater collection systems convey return flows to the disposal sites. Wastewater treatment plants treat the return flow to allowable standards for disposal. This is done to minimize the deterioration of the quality of the receiving water body or medium. The major function of urban drainage is collection and conveyance of storm-water to prevent flooding and the protection of vulnerable habitats. Mays (2009) describes these systems as "conventional urban water systems" (CUWSs). CUWSs can be primarily referred to as centralized and large-scale depending on the scale of the systems.

Overtime, CUWSs have been utilized for the provision of water sanitation in developed countries across the globe but less-developed countries are characterised by inadequate access to basic water and sanitation because of sporadic population growth, institutional capacity and financial difficulties (Stephenson 2001). CUWSs are characterised by less-effective and efficient technologies that have detrimental effects on the environment (Novotny et al. 2010). Hence, the drive toward utilizing alternative UWSs in situations where conventional systems fail to conform with the goals towards sustainability in terms of natural or financial resources (Shuping et al. 2006). According to Shuping et al. (2006), alternative urban water systems (AUWSs) largely depend on the availability of a conveyance network, treatment technologies and scale relevant infrastructure aimed at connecting the end user and alternative water sources. AUWSs are primarily designed to effectively and efficiently utilize resources in contrast to CUWSs. Some established alternative water management strategies include integrated water resources management (IWRM), urban water self-sufficiency (UWSS), water-sensitive urban design (WSUD) as well as water reuse.

2.3 Urban Water Management Strategies

To understand the concept of sustainable urban water management (UWM), it is imperative to clearly define what urban water management entails. Urban water management entails water supply, urban drainage, wastewater treatment and sludge handling (Larsen and Gujer, 1997). The concept of sustainability has been associated with a broad variety of anthropogenic activities relative to the use of resources such as natural, human and financial, implying long-term continuity and activity to carry on these activities (Marinova et.al. 2005). Concepts such as IWRM, UWSS, WSUD and water reuse, reclamation and recycling are considered as key components of urban water and wastewater management policies employed to tackle water scarcity and related problems around the world (Keremane and McKay, 2006).

2.3.1 Integrated Water Resources Management (IWRM)

IWRM is described as the practice of managing freshwater, wastewater and storm-water as components of a basin-wide management plan. It can also be seen as a flexible, participatory and iterative process which integrates the elements of the urban water cycle (UWC) with the city's urban development and surrounding basin's management to maximise economic, social and environmental benefits in an equitable manner. IWRM seeks to develop efficient and flexible urban water systems by adopting a diverse set of science and technology principles to ensure water security in urban areas. According to Savenije and Zaag (2008), IWRM takes into account the following four dimensions due to the nature of the water as shown in Figure 2.1:

1. Water resources can be referred to as the natural dimension. This includes all natural occurring water sources, such as water in rivers, lakes and groundwater. The natural dimension also takes into account water quality and quantity, stock

and flow and differentiating between different sources of natural occurring water cycle components such as rainfall, soil moisture, lakes, wetland and estuaries (Figure 2.1).

2. The water users (such as households, industries, agriculture ecosystem) take into cognisance the human element that is, social and economic groups and relevant stakeholders (Figure 2.1).
3. The spatial scale consists of:
   - Spatial distribution of water resources and utilization.
   - The different spatial scales at which water is being managed and the institutional arrangement and coordination that exists for these different scales. Examples of the different spatial scales are, individual or group, watershed, catchment area and river basins that cut across borders (Figure 2.1).
4. Temporal scales and patterns take into account the temporal variation in demand and availability of water resources. It also takes into consideration the physical structure built to balance out these variations in order for water supply to meet demand where necessary (van der Zang 2001).

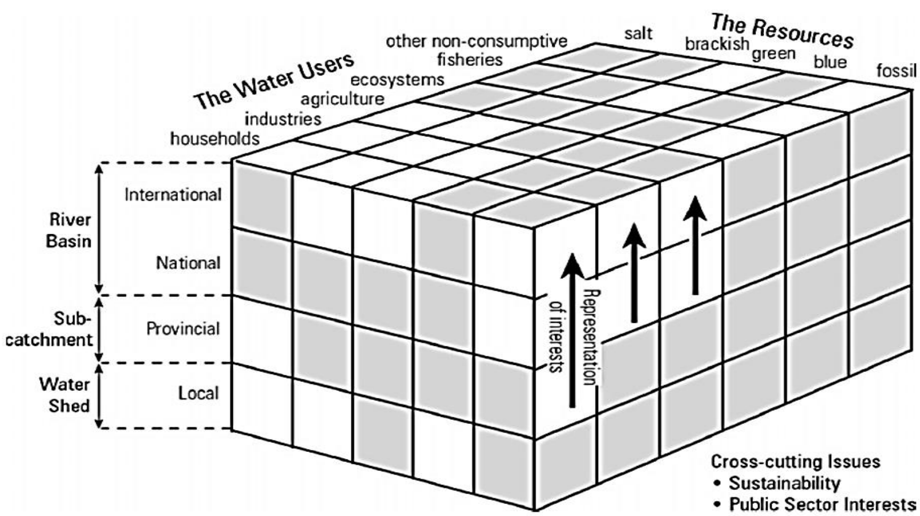


Figure 2.1: Three of the four dimensions of Integrated Water Resources Management (Savenije, 2000)

2.3.2 Water Sensitive Urban Design (WSUD)

Brown et al. (2008) defines WSUD as "an approach to urban planning and design that integrates land and water planning and management into urban design" and Wong (2000) defines WSUD as "the integration of urban planning and utilisation of best practices to achieve the objectives of sustainable drainage systems for urban areas". The concept of "WSUD is based on the premise that urban development and redevelopment must address the sustainability of water" (Engineers Australia, 2006). WSUD is based on formulating urban development plans that involve a pro-active process which recognises the opportunities for urban design, landscape architecture, storm-water management infrastructure and multiple storm-water management objectives to be intrinsically linked (Wong, 2000). .

2.3.3 Urban Water Self-Sufficiency (UWSS)

Han and Kim (2007) proposed a concept of urban water self-sufficiency as a measure to minimize urban dependency on importation of water. Urban water self-sufficiency can be defined as "the ratio of the amount of water sourced from within a given area which is limited to recycled wastewater, harvested rainwater or desalinated water from local shores to the total water demand in the same area" (Han and Kim 2007). It is imperative to establish a clearly defined system boundary. The definition highlights two important factors that self-sufficiency ratio is dependent on (i) the characteristics of the area under consideration (ii) defining a consistent system boundary. The geographical location boundary is suggested to be taken as the system boundary. UWSS can be evaluated by the following Equation 2.1.

$$UWSS = \frac{Q_{lr}}{Q_{td}} \qquad \textit{Equation 2.1}$$

Where Q_{lr} = the amount of water sourced from within a given area. It is restricted to recycled wastewater, harvested rainwater or desalinated water from local shores.

Q_{td} = the total water demand in the same area, e.g. a single building or a larger urban area.

2.3.4 Water Reuse

Water reuse involves the processing and utilization of partially or fully treated wastewater or effluent from a variety of sources (e.g. domestic, industrial, mining activities) for a new or different beneficial application such as drinking purposes, groundwater recharge, reservoir augmentation, industrial use or irrigation. The most important element of the water reuse concept is treated effluent from wastewater works. Treated wastewater is now considered by some as a new and reliable water source to supplement limited freshwater resources, without compromising public health (Asano 2001; Bahri 2001; Angelakis et al. cited in Madi et al. 2003; Murni et al. 2004 cited in Keremane and McKay, 2006). Every catchment area utilizes fresh water for various purposes which generate volumes of wastewater. Wastewater can be treated to a high level of purity with available treatment technology and placed in an engineered storage buffer/environmental buffer to augment imported water, recharge groundwater aquifers, agricultural irrigation purposes; land-scape watering, fire-fighting, and recreational purposes (Figure 2.2).

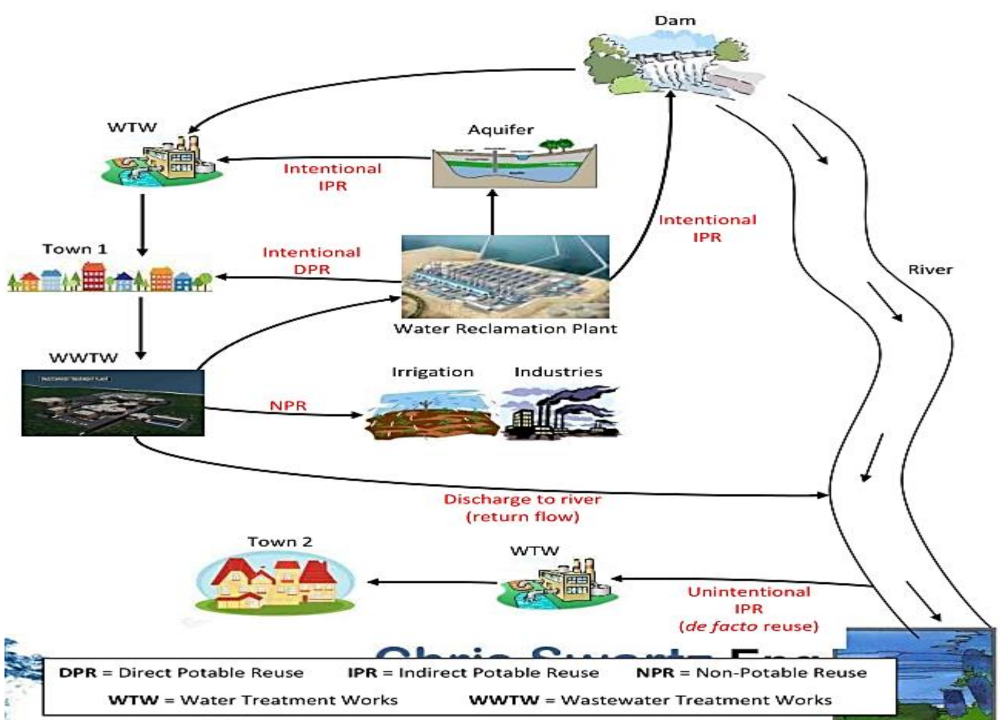


Figure 2.2: Schematic showing different types of water reuse (Swartz et al. (2014)

With increasing knowledge and benefits of water reuse potential, a number of water reuse initiatives have been successfully executed in many developed and developing countries (Chen et al, 2012). Non-potable water reuse opportunities have been exploited as a result of preference for non-potable applications such as agricultural irrigation, industrial recycling and reuse, and landscape irrigation as opposed to reuse for potable application (Leverenz et al. 2011). There are two main types of reuse projects namely non-potable reuse and potable reuse. For non-potable reuse, wastewater is treated to specific standards that fit for uses such as irrigation, industrial and landscaping but not for potable applications. Non-potable water reuse systems typically have lower quality objectives than potable reuse systems. The degree/level of treatment also varies depending on the end use.

2.3.4.1 Direct Potable Reuse: An Overview

Direct potable reuse (DPR) refers to the direct introduction of purified water commonly referred to as reclaimed/recycled water into the water reticulation network. Reclaimed water is derived from municipal wastewater, mine-water and rainfall runoff, which after extensive treatment and monitoring to ensure that drinking water quality standards are met at all times, feeds directly into a municipal water supply system (Leverenz et al., 2011). The treated effluent could be blended with source water to drinking water treatment plants for further treatment or introduced directly into municipal water reticulation systems.

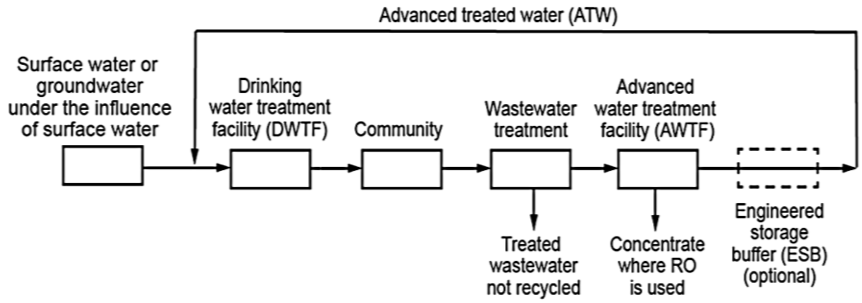
- ***Planned Potable Reuse***

There are two types of planned potable reuse. Firstly, direct potable reuse (DPR) in which wastewater is treated to drinking water standard and is introduced into the existing municipal water supply system. Secondly, indirect potable reuse (IPR) in which treated wastewater is introduced into an environmental buffer such as surface reservoir or groundwater basin before the bended water is introduced into a municipal water reticulation system.

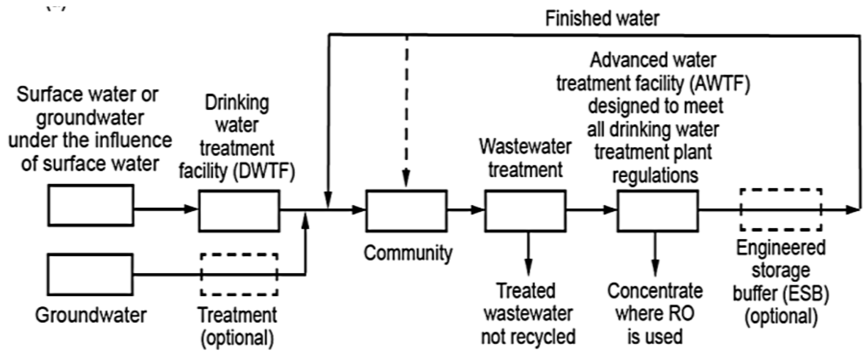
- ***Unplanned/Incidental Potable Reuse***

This is often referred to as de facto reuse. Unplanned potable reuse occurs when downstream surface water aquifers are subjected to upstream discharges of treated wastewater and the surface water aquifer is used as a raw water source for drinking water provision. Examples of this type of unplanned IPR is in the cities and towns along the Colorado River in the U.S and the Vaal river system in Gauteng, SA, where treated wastewater is discharged to surface and groundwater aquifers which are subsequently used for municipal water supply. In SA, dams, river and groundwater are water sources from which raw water for domestic uses are typically extracted. The extracted raw water is not fit for domestic applications; therefore it is treated to the required standard at a water treatment plant (WTP) before it is distributed to respective water users. Most raw water sources in SA are heavily polluted. This is as a result of diffuse pollution from the socio-economic of water metabolism at catchment levels and the indiscriminate discharge of poorly treated wastewater. This significantly affects the downstream water use as well as the complexity of the treatment needed to treat the water to a quality “fit-for-use”, for different relevant end users.

The apparent nature of this system means that multiple downstream water users are dependent on this water which may have been used by several upstream users, therefore indirectly becoming a recipient of recycled water. This type of reuse poses a significant potential risk to downstream water users because this type of reuse system is often not planned for or monitored. There are two types of DPR in existence today which involve highly purified water or finished water (i.e. wastewater that has undergone extensive treatment and monitoring to meet the required water quality standard for drinking water). Advanced treated water (ATW) can be described as treated effluent produced from an advanced water treatment facility (AWTF). Figure 2.3a shows the schematic for direct potable reuse with or without the use of an engineered storage buffer (ESB). The ATW is introduced into the drinking water treatment plant (DWTP) as a source raw water supply. Figure 2.3b shows highly purified water/ finished water with or without the use of an ESB introduced directly into the municipal drinking water supply system bypassing any form other of treatment or within the municipal water reticulation system. The introduction of ATW upstream from the DWTP makes the ATW essentially another raw water source.



(a)



(b)

Figure 2.3:Flow diagrams for DPR: (a) with ATW introduced upstream of a DWTF and (b) finished water introduced into the drinking water supply distribution system downstream of a DWTF. (WaterReuse Research Foundation, 2015)

Typically, the ATW is treated to meet the required drinking water quality standards and regulations, although it is not introduced into the municipal reticulation system unless it is permitted by legislations and the DWTP.

The DWTP serves as an additional treatment barrier for safety. According to Tchobanoglous et al. (2011), ESB are typically used before the ATW is introduced upstream in DWTP to serve as a water storage facility with a sufficient volumetric capacity to retain the ATW for a specific period of time. This is to ensure that the quality of the ATW meets all the required water quality and related public health standards or quality measures prior to introduction into a DWTP. The specific time period needed to retain the ATW in the ESB should be sufficient to allow for monitoring flow continuity, measurement and the reporting of specific constituents.

When an ESB is not used, the advanced water treatment plant (AWTP) should have the following; firstly, a redundant treatment mechanism to allow for the continuous production of ATW if one of the major treatment processes is out of specification. Secondly, effective and efficient monitoring to show and assure that sufficient treatment is carried out to ensure public health protection. Examples of DPR schemes are shown in Table 2.1below:

Table 2.1: Existing direct potable reuse projects in selected countries

S/N	Country	Location	Level of treatment	Application(s)
1	South Africa	Beaufort West	Water reclamation, with advanced treatment processes	Drinking water
2	South Africa	Emalahleni Local Municipality	Water reclamation, with advanced treatment processes	Drinking water
3	South Africa	Steve Tshwete Local Municipality	Water reclamation, with advanced treatment processes	Drinking water
4	Namibia	City of Windhoek	Water reclamation, with advanced treatment processes	Drinking water
5	U.S.A	Wichita Falls, Texas	Water reclamation, with advanced treatment processes	Drinking water
6	U.S.A	Colorado River Municipal Water District Raw Water Production Facility, Big Spring, Texas	Water reclamation, with advanced treatment processes	Drinking water

2.3.4.2 Indirect Potable Reuse (IPR)

In an IPR process, ATW or tertiary effluent is introduced into an environmental buffer which serves as a water storage containment facility before being extracted for potable applications. The environmental buffer is presumed to be at an in-situ advanced treatment unit to provide a loss of water identity and a measure of safety as an additional barrier for the protection of public health. However, the environmental storage of highly treated water, if not stabilized or mixed with other raw water source, can be contaminated (i.e. contaminants such as dissolution of metals from groundwater water aquifers or microbial and other contaminants from surface water aquifers. Figure 2.4a shows an IPR application for groundwater recharge (i.e. the environmental buffer is a groundwater aquifer). ATW can be applied by spreading or direct injection, whereas tertiary effluent is applied by spreading to take advantage of soil aquifer treatment. Figure 2.4b shows an IDR for reservoir augmentation (i.e. surface water reservoirs such as dams serve as the environmental buffer). Examples of IPR schemes implemented across the globe are shown in Table 2.2.

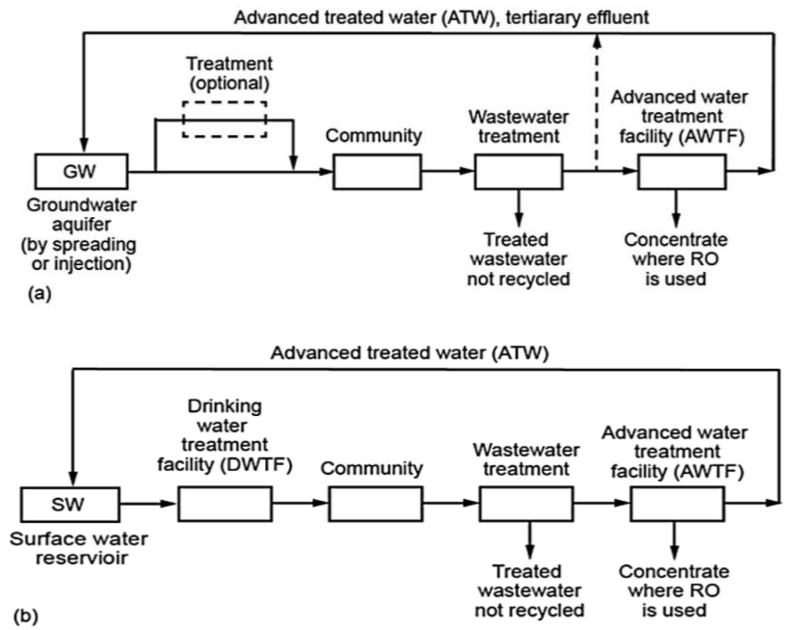


Figure 2.4: Schematics for IPR: (a) groundwater aquifer as an environmental buffer; and (b) surface water reservoir as an environmental buffer.

Table 2.2: Existing indirect potable reuse projects in some selected countries

S/N	Country	Location	Level of treatment	Application(s)
1	Belgium	Wulpen	Tertiary treatment	Groundwater recharge and saltwater intrusion
2	U.S.A	Orange County Water District, Fountain Valley, California	Tertiary treatment	Groundwater recharge
3	U.S.A	Upper Occoquan Water Service Authority, Virginia	Tertiary treatment	Reservoir augmentation
4	U.S.A	Cloudcroft, New Mexico	Tertiary treatment	Reservoir augmentation
5	United Kingdom	Waterwise	Tertiary treatment	Indirect potable reuse
6	Singapore	City of Singapore (NEWater)	Tertiary treatment	Industrial and potable water augmentation
7	France	Aubergenville	Tertiary treatment	Groundwater recharge

2.4 Sustainability, Sustainable Development and Sustainability Metrics (Indicators & Indexes)

2.4.1 Sustainability and Sustainable development (SD)

SD as defined by Becker (1997) and Sahely et al. (2005) is attaining a balance between three main goals: social, economic and environmental, across both spatial and temporal perspectives. Research by AwwaRF and CSIRO (as cited in Kenway et al. (2007)) and Gibson (2000), places emphasis on SD as dealing with environmental, social and economic concerns associated with inter-and intra-generations separately in an all-inclusive approach not as an add-on to the current management structure. This is important, as focusing solely on one goal or objective when making decisions regarding best practice, will lead to other effects becoming unrestricted. Therefore, problems arising from these effects will be transferred from an effect to another rather than having a general decline in problems.

The paradigm shift in sustainability assessment is such that inter-disciplinary activities and participation is required in decision making (Loucks et al. 2000). Sustainability implies widespread predicting of future actions and events based on present information. This can be termed “environmental accounting”. Environmental accounting hypothesizes that all factors and elements in a system are measurable and can be audited. This type of accounting could be biologically interpreted as Triple Bottom Line (TBL) analysis (social factors) or ecological footprint (Biological). The process of ascertaining progress in social, economic and environmental performance due to long or short term policy decisions is referred to as TBL (Waheed et al.2009). In TBL analysis, the environmental, financial and societal aspects of sustainability are analyzed based on the impact of policy decisions on these factors. In the analysis, the environment refers to the effect of policy decision on the natural environment (i.e. flora, fauna and natural resources), the economy refers to effect on financial sustainability, while society refers to the effect on the community in general (i.e. culture, public health and safety, social equity).

Based on the definition, sustainability may be referred to as “strong” or “weak”. Natural capital stock represents the sustaining of natural material assets development (Waheed et al.2009). Furthermore, Roseland (2000) and Jabareen (2008) stated that natural capital stock covers three categories: (i) non-renewable resources (e.g. mineral resources) ; (ii) the finite capacity of the natural system to produce ‘renewable resources’ (e.g. food crops and water supplies); and (iii) the capacity of natural systems to absorb the emissions and pollutants that arise from human actions without suffering from side effects which imply heavy costs to be passed onto future generations.

According to Waheed et al (2009), the condition of constant natural capital is normally termed ‘strong sustainability’. The assumption with regards to the concept of weak sustainability is that natural materials as well as services may be substituted with man-made goods and services, otherwise known as substitutability paradigm (Pearce and Turner, 1990). On the other hand, the assumption of the inability to replace services and natural materials is referred to as strong sustainability. Therefore natural capital is assumed to remain constant over time (Pearce and Turner 1990). This is also referred to as the non-substitutability paradigm. Both concepts have their merits and demerits. The problem with weak sustainability is that it is easy to quantify manufactured goods and assign monetary value to them, however, this it is not quite as easy or it may be impossible to do the same with natural services and materials. Furthermore, natural services and materials such as the ozone layer, wetlands or a river full of salmon cannot be substituted. Similarly, quantifying the worth of a forest full of trees poses a great challenge. One method may be assigning financial value to all trees based on them being transformed into furniture or paper. This does not however encompass other services forestry offers such as a refuge for wildlife, which affords hunters with food, as well as providing intrinsic benefits such as a pleasant natural environment for individuals and groups such as hikers. Hence these intangible services cannot be given a monetary value or substituted with any manufactured goods.

The concept of strong sustainability on the other hand, places emphasis on services that can only be provided by nature, which cannot be substituted. For example, the ecosystem service performed by the ozone layer will be extremely challenging for human beings to replace. It is clear that sustainability assessment is a developing notion which continuously raises the pertinent question of how sustainability can be efficiently measured. The question is addressed in the sections below.

2.4.2 Sustainability Metrics (Indicators and Indexes)

The quantitative measurement of sustainability has always been a problem. Hence to adequately assess sustainability, it may require different layers of input information such as goals, performance variables, assessment measures, indicators as well as indices as shown in Table 2.3. The main goals or objectives are usually identified by TBL (environment, social and economic performance). These are often identified by key groups of people and individuals including the public and beneficiaries of the service. Indicators or indices are assessment criteria that seek to identify underlying principles to determine if the set goals and objectives were achieved. The assessment criteria are used to establish a yardstick to which sustainability objectives are measured against. Assessment criteria are selected with regards to the context, degree and field of study.

Table 2.3: Sustainability matrices, an example in terms of TBL objectives (Waheed et al. 2009).

Data/ Variables	Indicators	Indices	Performance assessment criteria (C)	Objective (O)		
				Environment (O1)	Economics (O2)	Society (O3)
Basic data that can be directly measured or monitored.	Each performance indicator derived from aggregation of various basic criteria	Each performance criteria derived from aggregation of various indicators	Health (C1)	*		*
			Safety (C2)	*		*
			Economic development (C3)	*	*	*
			Social equity (C4)		*	*
			Environmental quality (C5)	*	*	*
			Ecology (C6)	*		
			Technical feasibility (C7)		*	*

***indicates the possible link between a specified criterion and objective**

In an engineering project for example, health, economic development, safety, environmental quality, technical feasibility, and safety could be the key assessment criteria.

The top-down and bottom-up approaches are used for defining performance assessment criteria. The bottom-up approach defines the aims in relation to baseline conditions (Waheed et al.2009). The assumption is that assessment criteria are established with regards to the sustainability condition (environmental, social and economic) under consideration. Hence, the assessment criteria are classified according to the sustainability baseline conditions. An example is environment as a baseline classification can have resource utilization and assessment criterion. TBL is categorized as a bottom-up approach. On the contrary, a top-down approach, which is also called the principles-based method, is of the assumption that sustainability is a state that society aims for, then sustainability criteria are used to define terms of the state that such a society is aiming for. The top-down approach is centered on the basis that assessment criteria are established from the sustainability principles, for example, the sustainability principle of biodiversity and ecological integrity criteria should advance biodiversity and ecological integrity and consequently sustain life. Gibson (2000) and Pope et al. (2004) argue that the top-down approach eclipses the bottom-up approach (TBL) due to the fact that it does not promote trade-offs but rather accentuates interdependencies between the sustainability dimensions while also evading some limitations of the TBL approach. Literature however has shown that wide-spread research has been carried out using both approaches.

Variables are used for assessing how successful a decision is in satisfying the assessment criteria requirements. Performance indicators/indices are established from these variables. These could be in reference to a context, location, conditions, actions or performance. These measures are needed in order to evaluate the state of environment by investigating several variables. The aforementioned variables could either be single valued or an aggregate (derived from the combination of two or more variables) to illustrate performance.

Sustainability indicator (SI) is an established approach through which the results of the quantitative assessment and the understanding of advancement made in achieving the goals of sustainable UWSs can be illustrated. Lundin and Morrison (2002), defines an indicator as "pieces of information, which summarize important properties, visualize phenomena of interest, quantify trends and communicate them to relevant target groups". Van Der Steen and Howe (2009) suggest that SIs provide information to assess the degree to which a specific sustainability objective has been attained. According to Gallopin (1997), the main functions of indicators are to provide early warning information, to assess trends and conditions, to envisage future trends and conditions and to provide information on spatial comparison.

Alegre (1999) summarized the fundamental features of performance indicators as:

- Inclusive of all pertinent facets of sustainability performance
- Can be easily understood as well as make deductions
- Abates the use of numbers
- Possible to authenticate
- Non-intersecting
- Assigned to a specific time period
- Have sufficient universality to be evaluated in various conditions

There exist a plethora of indicators for sustainability measurement from multiple research studies allied to the planning and management at different tiers of government, industries and institutions. Edwin (2002) investigated the task of deciding on the proper indicator to evaluate the changes in the environment due to the impact of the automotive industry activities. The key challenges with regards to selecting appropriate indicators stipulated by the study (Edwin, 2002) include: (i) development, selecting and evaluating suitable indicators with related functionality; and (ii) incorporating indicators into the automotive design and manufacturing processes and decision making processes. According to Edwin (2002), the application of a multi-objective decision making approach may well be difficult when assessing sustainability, especially if the indicators are not comparable or ambiguous. Singh et al. (2012) produced a comprehensive and concise synopsis of numerous sustainability indices which have been incorporated in policy practice as shown in Table 2.4.

Table 2.4: Summary of sustainability indices (adapted from Singh et al. (2012))

Research area	Name of index/indices	Component
Innovative, knowledge and technology indices	Summary innovation index (SII)	• Human resources • Knowledge creation • Transmission and application of new knowledge • Innovation finance, output and markets
Development indices	Human development index (HDI)	• Health • Knowledge • GDP per capita
Market and economy-based indices	Green Net National Product (GNNP) and System of integrated Environmental and Economic Accounting (SEEA)	• Natural resources • Economics • State of the environment, pressure and • Destruction
Eco-system based indices	Sustainability Performance index (SPI)	• Raw material • Process energy • Human and technological resources
	Ecological footprint (EF)	• Resource supply chain • Disposal management options
Composite sustainability performance indices for industries	Composite Sustainable Development Index (CSDI)	• Economics • Environment • Social performance
	Composite Sustainability Performance index (CSPI)	• Corporate citizenship • Environment • Economics
Product-based sustainability index	Life Cycle Index (LInX)	• Environment • Cost • Technology • Socio-political
Sustainability indices for cities	Urban Sustainability Index (USI)	• Urban status • Urban coordination • Urban potential
Environmental indices for policies, nations and regions	Environmental Sustainability Index (ESI)	• Environmental systems • Pressure, states, impact • Human vulnerability • Societal and institutional capacity • Global citizenship
	Environmental Performance Index (EPI)	• Environmental stresses • Human health • Ecosystem vitality • Natural resource management
Environmental indices for industries	Eco-indicator 99	• Human health • Ecosystem quality • Resources, minerals and fossil fuels

2.4.3 Sustainable Urban Water Systems

ASCE/UNESCO (1998) states that "*sustainable water resources systems" or "sustainable urban water systems" are those developed and managed to comprehensively add to the objectives of society, within the current climate but also in years to come now and in the future, while preserving ecological, environmental and hydrological integrity*". Sustainable water systems as defined by Pearson et al. (2010) are "water systems that satisfies changing demands (both human and environmental) placed on them now and into the future, whilst maintaining ecological and environmental integrity of water systems". Furthermore, these systems are expected to provide people living in urban areas with social amenities (e.g., water and sanitation) and also efficiently utilize resources with minimal impact upon the environment. According to Hellström et al. (2000), sustainable urban water system as part of any urban infrastructures ought to "progress towards a non-hazardous environment, preserve natural resources, foster health and hygiene, save financial and human resources." Some basic goals for sustainable UWSs put forward by Marsalek et al. (2008) are:

- The provision of safe and fit to drink water to consumers without interruptions at all times
- Waste-water management and control to protect and preserve the health of urban residents and the environment
- Runoff management to protect the environment from the adverse impact of floods and other pollutants
- The reuse of reclaimed water for beneficial purposes such as irrigation, aquifer recharge in the advent of water scarcity

2.4.4 Tools and Methods

Sustainability assessment can be described as a process whereby a specific system under consideration is assessed to obtain useful information on the system's performance at achieving the set sustainability requirements and goals. This assessment process is applicable to ranking fields of activities, providing information on the selection of appropriate optimum treatment technology as well as identifying possible solutions for development and implementation of designs (Shuping et al. 2006). The following section presents a brief description, review of methods and tools employed in assessing sustainability in an urban water system context. The next section describes some frameworks used for development and selection of SIs.

2.4.4.1 Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) Framework

MFA is a framework that analyses the movements of material (specific substance or classes of substances) in a system (urban water system) or spatial entity (urban economy) within a well-defined boundary. The framework helps analyse stocks and path flows of material/resources along with uses within a defined boundary which can be territorial, sectorial and company. Relative performance indicators are evaluated to measure the amount of resources utilized by processes within the system in order to optimize resources and material utilization efficiently. Basically, the mantra is to produce more with less. LCA framework is based on the same principle as the MFA but the LCA framework seeks to further account for the environmental impact of processes and/or systems such as technology, product or service from the resource extraction phase to the end of life phase. LCA is often called the “cradle to grave”. In strategic planning; LCA and MFA frameworks are often utilized for sustainability assessment process.

2.4.4.2 Objective Oriented Frameworks

Objective oriented frameworks are proactive frameworks that seek to assess the extent to which the achievement of a particular initiative/goal is considered to be beneficiary to a distinct sustainability condition. Strategic environmental assessment (SEA), LCA and United Nations’ millennium development goals frameworks are objective oriented and by nature proactive.

2.4.4.3 Sustainability Dimensions/Impact Driven Frameworks

Sustainability dimensions/impact driven frameworks centred on the effect of several actions in relation to the sustainability of a specific system. The TBL framework considers the outcome of the interaction between sustainability dimensions (environmental, social and economic) of an initiative. Environmental impact assessment (EIA) driven sustainability assessment is a typical example of the sustainability dimensions/impact driven frameworks. This implies that a system can have favourable outcome(s) in one dimension of sustainability, such as environmental dimension but less favourable outcomes in the other two dimensions. A defined threshold limit can be established to mitigate the detrimental impacts of the initiative. Examples of sustainability assessment frameworks that follow the sustainability dimension approach in various disciplines and unit of analysis include, water utilities (Ashley et al 2002), urban infrastructure development (Sahely et al 2005) and transportation (Litman 2008) etc. According to Pope et al (2004), the TBL approach embraces a reductionist approach to assessing sustainability. Such an approach disintegrated the sustainability dimension into three dimensions. This is applicable when the interaction between the three sustainability dimensions is not implicit. In some cases, one of the dimensions is found to be more important based on the analyst's perspective. In other cases, analysts have tried adding technical and/or institutional dimensions. One of the major merits of this approach is its flexibility and compatibility for development of a MCDM sustainability assessment.

2.4.4.4 Process driven or stakeholder participatory approach

A stakeholder participatory approach or process driven framework involves a planning process that provides an opportunity for incorporating stakeholders' values in creating their vision of sustainability. According to Jeon et al (2005), Motevallian and Tabesh (2011), stakeholders' participation is very essential to the planning and development processes in a community as well the process of integrating sustainability into development policies (e.g. Environmental Defence 1999). Stakeholders' participation is a key element that contributes significantly to achieving sustainability goals in community planning and development. A study by Velazquez et al (2006) suggested models to present a distinct take on the way individuals are responsible for sustainability initiatives, influence the shared behavioural change by endorsing consensus based sustainability goals and educating relative stakeholders for sustainable institutions and organizations.

2.4.4.5 Causal Chain/Linkage Based Frameworks

Causal chain/linkage based framework is established based on the notion of a cause and effect relationship. This framework seeks to provide a linkage between each element of the framework by outlining criteria for every factor and identifying effective actions to prevent and mitigate the effects. Examples of causal chain frameworks are:

1. Driving Forces-Pressure-State-Impact-Response (DFPSIR)
2. Driving Forces-Pressure-State-Exposure-Effect-Action (DFPSEA)
3. (PSR) Pressure-State-Response (PSR)

- **Pressure-State-Response (PSR)**

The PSR is typically based on the concept of a cause and effect phenomena. In 1994, the OECD developed the PSR framework to address the interaction between the society and the environment. The framework outlines the effect of anthropogenic activities that exert pressure on the environment which can induce changes in the quality of the state of the environment. Consequently, the society reacts to such changes in the state of the environment through economic, ecological as well as sectorial policies and/or programs (i.e. societal response) with the intention to avert or alleviate pressures exerted as well as damages to the environment. The PSR framework draws attention to these contributing chain/linkages thereby assisting decision makers, including the public to have a definitive view on the interaction between the environment, society and related issues (OECD 1999). The PSR framework is a widely approved framework adopted by organisations, institutions as well as government entities for reporting on the state of the environment (OECD 1999, World Resources 2005).

- **Driving Forces-Pressure-State-Impact-Response**

The Driving Forces-Pressure-State-Impact-Response framework is an extension of the PSR framework. The PSR framework was modified by the United Nations Commission on Sustainable Development (UNCSD) for the DPSIR framework. The DPSIR framework has been widely adopted by many for analyzing the cause-effect relationships between interacting components of the environment and humans. The DPSIR framework has been employed as an integrated approach for structuring and reporting environmental information which is useful in describing the origins and consequences of environmental problems (e.g. European Environment Agency (EEA) State of the Environment Reports and the European Statistical Office Statistical office). According to this framework, any form of development (social or economic) and natural conditions (driving forces) puts extra strain on the environment and this results in changes in the state of the environment. This may impact on the wellbeing and livelihood of humans, ecosystems and resources. This could result in a societal or government reaction that affects all the other elements. The DPSIR framework provides a platform to present the indicators needed to enable feedback to policy makers on environmental quality and the resulting impact of the political choices made, or to be made in the future.

- **Driving Forces-Pressure-State-Exposure-Effect-Action (DPSEEA)**

The DPSEEA framework was developed on behalf of the World Health Organization (WHO). It took a wider approach by incorporating the impact of driving forces which lead to pressures inducing changes in both the health and the state of the environment. It adapted the DPSIR framework by covering the cause and effects links from the condition of the environment through exposures to health effects; responses were labeled as actions. It also built on the idea of driving forces backwards to signify the role contextual factors such as social and economic development. In this way, the framework looks at the health effects as a result of these driving forces (such as anthropogenic activities, technology), which place an added burden on the environment in the form of production, consumption, waste generation and their consequent releases into the environment. These factors further place a negative effect on the environment and cause it to be altered (this includes issues such as environmental pollution or increased risks of natural hazards). When humans are exposed to these hazards, potential health risk are an eminent threats Engaging with policy and undertaking the necessary action would need to be taken into account in order to manage any potential health risks. These may be targeted at various points in the causal chain. Later interventions (focused on reducing exposure or alleviating the health impact) may seem to be more directly effective and at times more cost effective, because they can be targeted more directly at specific population groups and health outcomes. Preventative measures, in contrast, tend to involve rudimentary techniques. However, the appeal of preventative measures lies in the fact that it identifies the root of the problem and deals with that, as well as often offering a extensive range of other environmental and social benefits. The major value of the DPSEEA framework is its applicability and flexibility. The usefulness of the DSPEEA is dependent on the context in which is intended for use. Government agencies (European and New Zealand ministries of Health) and organizations (WHO) have used the DPSEEA framework for the development of environmental health indicators. The DPSEEA framework was consolidated as a viable framework for assessing the health impact of climate change as indicated in the February 2001 meeting in Victoria, Canada. Guidelines for the development of environmental health indicators were developed in the meeting with representatives from the WHO, Health Canada and UNEP in attendance. The main theme of the casual chain frameworks (especially DSPEEA) with regards to SD is based on the seven sustainability concepts ((i) ethical paradox; (ii) natural capital stock; (iii) equity; (iv) eco-form; (v) integrative management; (vi) utopianism and (vii) political global agenda) proposed by Jabareen (2008). These concepts ensure that resources are used effectively and efficiently at the cost of marginal TBL impacts. These concepts help promote and improve system performance (i.e. mitigating effect) without significantly compromising socio economic development through optimal corrective measures (i.e. remedial actions).

2.5 Methods for assessing Sustainability

Various system analysis approaches have been utilized in order to evaluate the sustainability of UWSs. Beck (1997) defined system analysis as "*the procedure and corpus of methods for providing support and guidance in the systematic analysis of decision-making problems*". System analysis can also be associated with the development and use of mathematical models for evaluating the optimal solutions to a problem". Life cycle assessment (LCA), Exergy analysis (EA), material flow analysis (MFA), microbial risk assessment (MRA) and multi-criteria analysis (MCA) are common examples of system analysis methods used for UWSs sustainability assessment process. The next section discusses the following sustainability assessment methods (MCA LCA and MRA) and studies that they have been utilized in.

2.5.1 Life Cycle Assessment (LCA)

Curran (1996) describes LCA as an approach that evaluates the links between any given activity and its effect on the environment, starting from extraction of raw materials from nature to perform the activity to the point at which all materials are returned back to nature. International organizations such as UNEP and International Standard organization (ISO) have promoted the use of LCA through their scientific research (Guinee et al. 2004). For example, ISO has incorporated LCA methodology in the framework of ISO14000 series (Jeppsson et al. 1999). According to Guinee et al. (2004), LCA consists of the following steps:

- **Definition of goal and scope of study/system:** This addresses development objects for the study/system under consideration in the form of questions that need to be answered, specific area of application and establishment of system/study boundaries (spatial or temporal) respectively.
- **Analysis of inventory:** This procedure entails accounting for the flow of materials through the system throughout its life cycle. Raw materials utilization, energy and releases into the environment are included in inventory analysis.
- **Impact assessment:** This involves aligning process performance data gathered with associated specific environmental impacts to illustrate the link between processes and their effects.
- **Interpretation:** This is the concluding phase of the LCA process where the soundness and robustness of results are analysed.

Examples of studies that utilised LCA to assess the sustainability of UWSs include Lundin and Morrison (2002), Lundie et al. (2004 and Mahgoub et al. (2010).

2.5.2 Microbial risk assessment

According to Fane (2004), UWSs main function is to facilitate the provision of safe water and sanitation, but they can pose threats to the health of humans and the environment if not properly managed by serving as a conduit for pollutants found in raw water sources. Hence, evaluating the degree of microbial risk to UWSs in a quantitative manner is imperative. Craun et al. (1996) first presented a systematic framework to evaluate risk to human health due to pathogens. MRA is an analytical technique which seeks to evaluate the possibility of infection in relation to contact to pathogenic microorganisms (Fane 2006). This involves the application of dose response function to describe the link between the pathogens ingested and the probability of infection so as to envisage the degree of risk from exposure with regards to a probability distribution function of contamination (Fane 2006). In Australia, MRA has been utilized to measure the sustainability of UWSS in several regions such as wastewater treatment system options as well as the source and corresponding risks of recycled water (Fane 2006; Ashbolt et al. 2004 and Chen et al. 2011).

2.5.3 Multi-Criteria Analysis

Lundie et al (2005) define Multi-Criteria Assessment (MCA) and Multi-Criteria Decision Aiding (MCDA) as both integrative tools for the other sustainability analytical and assessment tools and a potential means for stakeholder engagement. This framework emphasizes the incorporation of direct consultation with stakeholders from the outset of project development. Knowing exactly who the relevant stakeholders are and their involvement in the planning process has to do with the magnitude of the problem and its probable solution (Lundie et al, 2006). The use of MCDMs for integrated sustainability assessment is on the increase and becoming widespread (Mosadeghi et al. 2013). All MCDM techniques entail a multi-stage or multi-part process involving the definition of objectives, selection of criteria for measuring objectives, specifying alternatives, assigning weights to the criteria, applying the appropriate mathematical algorithm for ranking of alternatives and selecting the best alternatives (Herath and Prato, 2006; Ananda and Herath, 2009; Mosadeghi et al. 2009). According to Asgharpour (1998), there are two main classes of MCDMs namely, multi-objective decision-making methods (MODMs) and multi-attribute decision-making methods (MADMs).

MODMs are basically designed to find an optimal solution to an optimization problem, while MADMs are designed for selection of the best alternative to a selected problem (Asgharpour 1998). Typical examples of MODMs include Compromise programming (CP) and Goal programming (GP). Technique for order of preference by similarity to ideal situation (TOPSIS), Analytical hierarchy process (AHP), Elimination and choice expecting reality (ELECTRE), Novel approach to imprecise assessment and decision environments (NAIADE), and Preference ranking organization method for enriching evaluations (PROMETHEE) are typical examples of MADMs (Motevallian and Tabesh, 2011). MCDMs can be designed for single (i.e. individual) or group decision making. Group decision making MCDMs are designed to combine different assumptions and outlooks for problems from multiple decision makers. Case studies of the application of MCDM methods in urban water management problems are reviewed in studies by Motevallian and Tabesh (2011) and Lai et al, (2008).

2.6 Sustainable Urban Water Management: Implementation and experiences

To achieve objectives goals of sustainable UWSSs, a fundamental prerequisite is the adoption of sustainable practice for managing these systems. Van de Meene et al. (2011) describes SUWM as "*integrated and biophysical systems, which consider social, economic, environmental and political contexts, provision of water for ecological and human uses and a long-term perspective*". The sections below describe some examples and experiences of SUWM practices in some regions across the globe.

2.6.1 SWITCH: Toward the city of the future

SWITCH stands for Sustainable Water Management Improves Tomorrow's Cities Health (Van der Teen and Howe, 2009). SWITCH is a research programme developed by the European Union (EU) and co-sponsored by a syndicate of 33 associates from 15 countries from 2006 and 2011. The key goal of the program was on how to facilitate and accommodate the transitioning of existing SUWM infrastructures into the "city of the future" (Van der Teen and Howe, 2009). Across the globe, IUWM is the general form of SUWM applied to UWSs. According to Mays (2009), the term "integrated" suggests the combination of the various components of UWM and considering UWSs as a single entity. Van der Steen and Howe (2009) hypothesized the design and management of UWSs that is established on exploration and optimization of the whole UWS (infrastructure and human organizations, water supply, sanitation and storm-water) will result on more sustainable solutions than the optimization of distinct elements of the system". According to Mays (2009), two reasons for applying IUWM to UWSs include, different components of UWSs are naturally linked through the hydrological cycle and the benefits of these components can fully be actualized through a consolidated management of these systems as oppose to managing them independently. Three main parts of the SWITCH program highlighted as described by Van der Teen and Howe, (2009) are outlined below:

- Learning alliances: This was proposed when it came to dealing with complex situations. Butterworth et al. (2011) suggested that experts working as a group can arrive at a more robust solution to a problem rather working separately. Examples of "SWITCH cities" involved in learning alliance include Accra, Beijing, Belo Horizonte, Birmingham, Hamburg, Lima, Lodz, , and Zaragoza (Van der Teen and Howe, 2009).
- Action research: This involves moving from the developmental phase to actual implementation of IUWM in cities as case study sites which are examples of "SWITCH cities."
- Multiple-way learning: This is based on the premise that through the case study sites, experiences and information can be shared by experts and decision makers in the water sectors from developing countries and European countries.

2.6.2 An Australian approach to integrated resources planning

Fane et al. (2011), describe Integrated Resources Planning (IRP) as "*a process of planning services in a way that ensures the efficient and sustainable management of water, energy, or other resources*". IRP entails creating comprehensive demand predictions, generating a plethora of options, unbiased estimation of demand and supply options and determining the optimum sustainable option to satisfy the demand–supply requirement (Fane et al. 2011). Turner et al (2008) in their study describe an example of an IRP framework developed for UWM in Australia. The basic principles of an IRP framework as described by Sushil (1993) are highlighted below:

- Water service provision: This takes into consideration the fact that water users are more concerned about the services water is utilized for and not the resource itself.
- In depth demand projecting: An end-user investigation is carried out to breakdown water demand which enables demand projection and water conservation.
- Exploring a wide variety of feasible alternatives to meet service requirements: The objectives of IRP can be achieved by exploring feasible alternatives such as water reuse and rain water harvesting to augment water supply.
- Comparison of alternatives using general measures, assumptions and a boundary: In order to ensure the selection of the lowest cost option for water services, the net present value was adopted by the IRP to assess all options.
- A participatory approach: IRP recognizes the importance of relevant multi-disciplinary stakeholders' involvement through the planning process in order to have a robust final decision.
- Adaptive management: This emphasises the fact that IRP is a progressive and iterative learning practice involving the development of strategies, their implementation as well as outcomes assessed.

2.6.3 The Soft Path for Water: An illustration of the practice in Canada

Lovins (1977) introduced the "*soft path*" concept as illustrated in the publication titled "*soft path for energy*". According to Lovins (1977), humans need the services provided by energy sources (such as fuel, natural gas and coal) not the actual resources. The "soft path" concept was adopted by Wolff and Gleick (2002) to create the "soft path for water" in the context of water resource management. Wolff and Gleick, (2002) argue that the conventional "hard" path basically depends on centralized infrastructures. Furthermore, in decision-making and adopting water supply management practices, there is a soft path to satisfy water-related requirements through efficient conservation of water as well as meeting users' diverse requirements. This method is termed a "*soft* *path*" as it basically depends on human innovations for solving water-related challenges (Brandes and Brooks, 2006). The principles of "soft path of water" by Brooks (2005) highlighted the following:

- To resolve the gaps between water demand and supply from the demand perspective: This principle stresses that before any effort explore new water supply source to the current system, it imperative that all possible water conservation efforts have been exhausted.
- To ensure that the water quality and quantity demanded by different end users is met, Fane (2006) refers to this as, "water quality cascading" which suggests that it is imperative to first address the needs associated with drinking water meeting the required standards than water supply for non-potable applications.
- Back-casting rather than forecasting: Back-casting begins with the desired future, then working backwards to ascertain the "soft paths" that link the present condition to that future condition. Hence, the major goal of planning is to ensure that the objectives of the system can be achieved. The planning objective is not focussed on ascertaining where the current system leads to.

According to Brooks and Holtz (2009), the following steps describe how to perform the water soft path analysis:

- Identification of all water services: Create a list that takes into account all activities (e.g. drinking, bathing and washing) that consumers use water for and estimate the volumetric water requirement for each activity. All potential water saving options are explored and estimated.
- Creation of a "*business-as-usual scenario*": This entails development of scenarios in which the rate of water withdrawal and consumption increase over a period of time stipulated for the study while assuming a normal growth rate for the population and economy.
- Appraisal of water supply options: Identification and evaluation of all current freshwater water sources to determine if any are being over exploited. Any alternative water supply source that poses a threat to the well-being of humans and the environment should be rejected.

- Establishing an anticipated future scenario: The assumption in the anticipated future scenario is that in the target year, water consumption rate and supply sources have to be sustainable. Engagement with stakeholders may be helpful in the process for identifying the ideal options for the anticipated future scenarios.
- Ensuring that the projected scenarios are sustainable: At this stage, the ideal projected scenarios are analysed and modified to ensure the water is able to satisfy water demand in a sustainable manner.
- Alteration to accommodate envisaged impacts of climate change: In this phase, the anthropogenic and climate change impact ought to be integrated into future scenarios analysis.
- Back-casting from the anticipated ideal conditions to the real present conditions: At this stage, several soft paths are developed by designing programs and linking the ideal future to the present condition. This will create a clear picture of actions to be taken to achieve the anticipated ideal condition.

Brooks et al. (2009), in conjunction with Friends of the Earth, Canada, and researchers from three Canadian universities applied the water soft path analysis framework to some locations in Canada at an urban, watershed and provincial spatial scales.

2.7 Sustainable Urban Water Management: Issues that need to be addressed

Although a plethora of studies have been carried out within the framework of SUWM, some areas of concern discussed below require attention and should possibly be considered for future research studies:

2.7.1 Climate change effects on urban water systems

Many countries and regions across the globe are experiencing changes in weather patterns and climatic conditions such as rainfall patterns, flash floods and droughts which have a major impact on the water cycle. The hydrological cycle is the primary medium through which climate change influences the ecosystem thus impacting the well-being and livelihood of communities. Studies have shown that there are significant links between trends in temperature or rainfall and some ecological indicators of river flows. One major remark from the Fourth World Water Forum (2006) and the

Cooperative Programme on Water and Climate (CPWC) is the fact that potential risks presented by variations in weather conditions are not being sufficiently engaged with in the development, planning, as well as implementation of water resources management strategies (Mays 2009). Mays (2009) argued further that even in developed countries like the United States of America; the topic of climate change has not been given adequate consideration with regards to urban water resources management. This could be addressed by the modification of urban water planning models with the intention of incorporating the observed impact of climate change.

2.7.2 A need for a paradigm shift in tackling the problem of sustainability

An appraisal methodologies and tools employed for UWSs sustainability assessment exercises from previous studies indicate that a "*hard systems thinking*" approach was adopted by these studies. Checkland (1981) describes, "*hard systems thinking*" as "*an approach to real world problems in which an objective or end-to-be-achieved can be taken as given*." This implies that there is an anticipated state of a phenomenon and a current existing state of that phenomenon as well as deciding the most appropriate way of getting from the current state of the phenomenon to the preferred state of the phenomenon (Checkland 1981). According to Pahl-Wostl (2002), decision-making centred on the hard system thinking approach entails choosing an alternative among a distinct set of alternatives for action. From the sustainability perspective, an example of an analytical approach based on the hard system thinking approach is the multi-criteria analysis (MCA) employed for the selection of an optimum alternative for a specific UWS.

Vob et al. (2006); Bagheri and Hjorth (2007) critique the use of the hard systems thinking methodology for assessing how sustainable a socio-economic is. Socio-economic systems such as UWSs are characterised by complex and non-linear behaviour as they typically comprise of a plethora of exchanges and response cycles. Taking this into consideration, implementing predictable linear methods such as the hard systems thinking approach is rationally not the most effective way to address these challenges of such intricate nonlinear systems. Contrariwise, a "*soft system thinking*" approach is, "*an action oriented process of inquiry into problematic situations in which users learn their way from finding out about the situation, to taking action to improve it*" (Checkland and Poulter, 2010).

Sushil (1993) argues that embracing the paradigm of "learning" (which the "soft systems thinking" method is centred on) is a more appropriate tool to methodically study and assess intricate socioeconomic systems in comparison to the "optimization" paradigm. Thus it serves as an alternative approach to dealing with management problems. "Social learning" is an example of a soft system thinking-based approach that has being gaining attention and recognition in the field of natural resources management. Pahl-Wostl and Hare (2004) defined the social learning as, "an on-going learning and arbitration practice that gives a lot of priority to sharing of perspectives, questions of communication and developing adaptive group strategies for problem solving". A limited number of studies have been carried out the employ the use of the social learning concept to address the problem of sustainability in UWSs (Bagheri and Hjorth 2007, Pearson et al. 2010). A study by Bagheri and Hjorth (2007) used a combination of system dynamics approach and social learning concepts to evaluate the progress of intricate systems (UWS) toward SD which in Tehran. The result of the study indicated that adopting the social learning concept is an appropriate alternative for development of sustainable UWSs. However, more research needs to do be done to encourage the general acceptance of the concept in UWM development.

In SA, the adequate provision of water to the citizenry is one of the critical challenges facing the country. The economic hubs of the SA are characterised with increasingly rapid urbanization which if not properly managed can become a key driver for increased water demand. Evidently, alternative systems-based approaches need to be explored while ensuring that water that meets the quality required standards is provided to meet growing demand. According to Armitage et al, (2014), a systems approach with multiple objectives is needed (i.e.one that takes into account (i) community values and aspirations when dealing with water supply; (ii) wet and dry sanitation; (iii) biological and chemical treatment of associated contaminants; (iv) drainage and the management of industrial effluents), while recognizing the different users (such as residential, institutional, commercial and industrial). An integrated systems-based approach such as this has the potential to facilitate a change in urban areas from "water-wasteful" settlements to "water-sensitive' settlements" (Armitage et al, 2014). A "settlement" is to be generally understood to comprise a concentration of people within a specific area and serviced by some public infrastructure and services (Armitage et al, 2014). The study by Armitage et al, (2014) in conjunction with the Water Research Commission (WRC) was aimed at providing strategic guidance to urban water management decision-makers (such as city managers, municipal and provincial authority officials) on the practicality and applicability of WSUD in a South African context. The study Furthermore the study by Armitage et al. (2014) was aimed at defining what 'water sensitivity' might mean within the SA context which entails expanding the definition of 'city' in water sensitive city to include a broader array of settlement types so as to motivate the adoption a context-specific vision for water sensitivity. In this regard, Armitage et al. (2014) suggested a strategic framework with four different components to facilitate transformation to Water Sensitive Settlements (WSS) in SA, and provides guidance on the various WSUD strategies that could be adopted to achieve this, as well as giving an indication of appropriate modelling tools. Armitage et al. (2014) carried a policy review on institutional and legal issues, hence, obstacles to WSUD were identified and recommendations were provided on how these obstacles can be addressed.

2.7.3 Capacity development in private organizations, society and institutions (government, academic)

The UNDP (2009) briefing paper describes capacity development (CD) as, "*the process through which individuals, organizations and societies obtain, strengthen and maintain the capabilities to set and achieve their own development objectives over time*". CD can be addressed at three interrelated stages as illustrated in the UN (2006) published document on governance and public administration:

- Individual stage: At this level, CD entails providing appropriate mechanisms to facilitate government representatives' ability to initiate and participate in on-going learning processes, acquire new knowledge and skills as well as their applications.

- Institutional level: At this level, CD focuses on updating systems and processes to be in tune with the latest innovations.
- Societal stage: At this stage, CD seeks to develop a more interactive approach to public administration which draws knowledge from engagements and feedback obtained from the public at large. A number of pilot studies as well as researches have been carried out to facilitate sustainable practices in UWM. However, in developing countries, sustainability and its objectives is still not fully taken into consideration by relevant stakeholders in the water sector. This inability on the part of relevant stakeholders to adopt sustainable practices in UWM can be attributed to poor CD in institutions (academics and governmental), private enterprises as well as the larger society. Figueres (2005) investigated the challenges facing UWM in Central Asia and Middle Eastern countries. The study concluded that there is a pressing necessity to build capacity of staff within the countries where the study was carried out. Hence, more effort must be committed to training and capacity building of relevant stakeholders on sustainability practices in UWM (Figueres, 2005). The UNEP (2006) report on capacity building for SD highlighted vital strategies that can be adopted to facilitate the effectiveness of capacity building. These strategies are: (i) identification of limitations and building on existing capacity framework (ii) having a well-defined objective, (iii) exploring and application of multiple capacity building methodologies, (iv) training the appropriate individuals (v) facilitating the "training-of-trainers" technique (vi) mandatory capacity building training in relevant institutions at all levels (national or regional).

2.7.4 A South African Context

Owing to the history of South Africa, one of the major challenges facing the South African government is the equitable and reliable supply of adequate drinking water to the citizenry. South Africa is a semi-arid country due to the low volumes of rainfall (average of 500 mm per annum) and high evaporation (approximately 85% of the mean annual precipitation) (Adewumi 2011). The uneven distribution and highly variable nature of rainfall across the country contributes to water being surplus in some areas and limited in others. South African rivers are characterized with relatively low flow levels for the significant part of the year. However, infrequent high flows do occur over limited periods, which often is unpredictable. According to DWAF (2004), most of the rivers in SA are not navigable and the combined flow of all the rivers in the country amounts to about 49000 million m^3 annually. SA has about 320 major dams with each exceeding one million m^3 resulting in a total capacity of not less than 320 million m^3 (DWAF 2004). SA is currently classified as a "water stressed" country as defined by the Falkenmark indicator. 77%, 14% and 9% of the sectorial water requirements is met using surface water, return flow and groundwater respectively (DWAF, 2009).

Several anthropogenic and developmental activities such as urbanization, afforestation, mining and bulk industries have contributed to the deterioration the water quality in South African rivers and reservoirs as these supply systems support the social and economic development in the country (Carden 2013). A significant example is the eutrophication of surface water bodies and reservoir systems. In SA, for the past 40 years, eutrophication has become an increasing threat to the usability of available freshwater resources (Van Ginkel, 2011). The South African Institution of Civil Engineers (SAICE) Infrastructure Report Card of 2011 on water infrastructure especially wastewater management infrastructure found "persistent, significant salinization of key river systems and eutrophication in many water bodies and reservoirs. These problems aggravate the cost of water treatment, infrastructures and damages to the environment. The infrastructure report card also notes that "focus on water quantity, not quality, makes water services unsustainable" and that there are "serious problems with management of many wastewater (sewage) treatment works. Wastewater leakage and spillage, especially into major rivers, is still too high" (SAICE, 2011). However, the report by Muller et al. (2009) on ensuring water security in South Africa indicated that there is no reason for SA to experience water scarcity if the existing water infrastructures and systems are managed efficiently and effectively while the country is still facing various challenges brought about by the limited and variable nature of its water resources. Carden (2013) highlighted some challenges facing integrated water resources planning for SA as shown in Table 2.5.

Table 2.5: Critical issues associated with Integrated Water Resources Planning for SA (Carden 2013)

Challenges	**Opportunities/Actions**
Water quality deterioration through pollution from agricultural, industrial and mining activities, and poor urban wastewater management	• *Treatment and reuse of poor quality water to solve supply and quality issues* • *Increasing technical skills*
Meeting new demands from storage and transfer schemes may prove too costly for SA in the future	• *Assessment of how water is used by different sectors* • *Investing in Water conservation/water demand management* • *Exploring new and unused resources, and changing uses– groundwater, effluent reuse, desalination*
The energy sector requires water at the highest assurance of supply	• *Managing growth in line with available water resources* • *Addressing forward planning and implementation*
Irrigated agriculture is SA's biggest user of water	• *Additional ways of making water available to small-scale farmers, such as rainwater harvesting*
Ecological Reserve not being met in many areas	• *Water to be taken from existing users, or provided from newly developed resources*
Climate change impacts	• *Monitoring water resources – hydrology, climate, availability and use*

According to Claassen (2013), the management of water resources in SA has moved from a focus on private good, with a strong role of the state and institutions to a greater emphasis on public good and a network approach. Although this paradigm shift has yielded some short term social and economic benefits, the sustainability of water resources has been compromised. Claassen, (2013) explained further that the challenges in implementing progressive legislation is reflected in a shortage of skilled people, weaknesses in management instruments and difficulties in finding a balance between the role of the state and institutions and the effective function of networks to achieve development outcomes. On the other hand, the implementation of institutional roles and functions has started to yield results, but is still some way from the transformation and capacity envisaged in the South African National Water Act (Act 36 of 1998) (Claassen, 2013).

2.8 Summary

This chapter contains a review of the important topics associated with the concept of sustainability in UWSs, a description of the functions of UWSs, current practices and definition aim and objectives of sustainable UWSs. Furthermore, conventional techniques and tools employed the sustainability assessment process of UWSs sustainability assessment process were discussed.as well as practices of SUWM in countries around the globe. Moreover, this chapter illustrated valid concerns that need to be addressed by future research. Over the past decades, the principles of sustainability in UWSs have been well recognised in terms of meanings, theoretical frameworks and analytical approaches. However, there is need for considerable efforts to make these principles work in reality. According to Gleick et al. (2005), approximately 1.1 billion people do not have access to safe drinking water; about 2.6 billion live without proper sanitation facility and between 2 and 5 million individuals lose their lives annually due to water-related ailments. On a global scale, there is still a long way to go when it comes to implementing and adopting the concept of sustainable practices in UWSs management to facilitate accessibility to adequate water and sanitation. In order to facilitate progress towards the SD of UWSs, more efforts need to be allocated to developing mechanisms that will encourage the involvement of stakeholders in the decision-making process. This will enable these stakeholders to communicate their visions of sustainability as well as draw knowledge from their shared experiences in water resources management to make informed decisions from these interactions.

CHAPTER 3

3 PREDICTION OF USABLE RETURN FLOW POTENTIAL: A LINEAR REGRESSION MODELLING & BAYESIAN NETWORK APPROACH

3.1 Introduction

Water reuse has attracted growing attention across the globe as a vital part of water resources management forming an essential component of water demand management. Water scarcity challenges linked with the increase in population, deterioration of surface water quality, climate change and depletion of groundwater among other factors drive the need for exploring alternative water management strategies (Chen et al, 2012). In South Africa, close to 5.7 million people do not have access to basic water while 17–18 million lack access to adequate sanitary facilities and most effluent discharge and urban run-off are not reused (Swartz et al. 2016). With increasing knowledge and understanding of the potentials and advantages of water reuse, direct and indirect potable water reuse schemes have being successfully implemented in some developed and developing countries (Leverenz et al. 2011). Ilemobade et al. (2012) indicated that increase in socio-economic development of South African communities has led to an overall increase in water demand for various purposes.

The recorded Standard Precipitation Index (SPI) from October 2012 to September 2013 shows that South African communities are becoming susceptible to drought conditions. These conditions were noticeable in the drought-prone areas in the North West, Free State, and Northern Cape provinces (Weather SA, 2014). The dams in the North West and Free State provinces recorded low storage as an indication of deficient rainfall leading to dry conditions (DWA, 2014). The adverse climatic conditions resulted in the critical shortage of potable water and damages to crops to the point of that the North West province was declared a state of disaster from the drought. Recently in mid-2015, South Africa recorded the worst drought which was caused by an El Nino weather system that swept across southern Africa which threatened agricultural activities within the country. The drought condition contributed to the on-going economic slowdown, threatening near-zero growth if not a recession in 2016. The Western Cape Province is experiencing a critical drought which is seriously impacting the agricultural sector across large parts of the province. Low winter rainfall over the last three years, coupled with high temperatures and evaporation, has resulted in extremely low dam levels in most areas. Furthermore, rapid urbanisation, population growth and increasing economic activity in water-scarce areas of the province are placing pressure on the limited water resource. Invariably, the implementation of water reuse schemes seems inevitable in many South African communities especially those faced with declining freshwater availability (Ilemobade et al. 2012). However, the quantity of usable return flow described as wastewater that can be harnessed for reuse is subject to several factors, ranging from environmental to technical, socio-economical, environmental and institutional (Yang and Abbaspour, 2007).

Chu et al. (2004) employed a linear programming optimization approach to investigate wastewater reuse potential taking into consideration physical and economic constraints linked with regional disparities in China. The study assumed a linear relationship between the model variables but in reality, this not the case. Environmental factors (such as weather conditions, water consumption rates, sectorial water requirements, degrees of uncertainty and spatial variability with time were not taken into consideration. Yang and Abbaspour (2007) applied a linear programming approach for estimating wastewater reuse potential in relation to quantity influencing constraints and driving factors in China. The model was used to evaluate different reuse scenarios in relation to cost implications. However, the model did take into consideration the degree of uncertainty associated with the parameters that influences water reuse potential included in the model. Hochstrat et al. (2005) developed a mass balance approach to estimate urban water reclamation and reuse potential within a European context. The approach employed the water management data such as water availability, water demand and treated effluent in its analysis. Future projections were carried out using the available volumetric information on the current water reuse potential influencing parameters. However, the outcome of the model disregarded variation in natural water resources distribution within a country and socio-economic objections against implementing wastewater reuse. Alfarra et al. (2011) developed a wastewater reuse index (WRI) which is defined as "the ratio of the actual wastewater reused to the overall wastewater generated". The WRI was used to quantify the actual proportion wastewater reused from the overall wastewater generated to facilitate a better insight into reuse efficiency challenges. Alfarra et al. (2011) argued that the WRI better reflects wastewater reuse potential as compared to the generally used ratio of reuse to overall wastewater treated. However, the WRI cannot be used to project future trends in water reuse potential.

Adewumi et al. (2010) presented an overview and quantitative analysis of the South Africa's water resources situation in order to put the need for wastewater reuse into perspective. The analysis undertaken established that only a minute fraction of wastewater potential is actually exploited the country. The study highlighted some valuable experiences of wastewater reuse in SA and also presented a strong argument for the broader implementation of water reuse initiatives. Almeida et al. (2013) developed a fuzzy inference system to estimate water reuse potential in 155 regions and 183 cities across the globe. The study observed that water reuse potential could be linked to environmental factors such as drought, water exploitation, water use, population density and the wastewater treatment rate, among others. However, the rules guiding the fuzzy inference system are subjective, and this calls to question its accuracy. Furthermore, any change to the membership function or introduction of one/more variables results to a change in the rules which invariably alters the outcomes. Each parameter/variable choice affects the others which create a multi-parameter optimization problem in the system.

A review of the above studies indicated that various methods have been applied to estimate water reuse potential including mathematical programming (linear programming), qualitative survey analysis, fuzzy inference system, and other various modelling approaches. Hence, a Bayesian Network modelling approach was adopted in this study. In the field of natural resources management and environmental sciences, Bayesian Networks have proven to be an appropriate approach for ecosystem modelling (Rositano and Ferraro 2014; Garcia et al. 2013), climate change impact assessment

(Richards et al. 2014; Mantyka-Pringle et al. 2014), watershed management (Yang et al. 2007; Barton et al. 2008; Keshtkar et al. 2013; Shenton et al. 2014). According to Mamitimin et al. (2015), this approach has the ability to clearly explain intricate relations between variables, easily compare scenarios, and determine the critical influencing system variables with regards to natural resources management under intricate conditions. Another key benefit of this approach is its flexibility with regards to data sources. In situations where data is limited/not available, BN approach can implicitly integrate relevant data from different sources such as data from the literature, empirical data, expert and stakeholders' knowledge (Uusitalo 2007, Gret-Regamey et al. 2013). This study seek to contribute to researches on water reuse initiatives by using water resource variations, weather conditions and ecological requirements to estimate water reuse potential in South African water management areas. Hence, this study presents a linear regression and Bayesian Network (BN) modelling approach for predicting water reuse potential in South African water management areas.

3.2 Multi-Criteria Decision Making (MCDM) and Bayesian Networks

Multi-Criteria Decision Making (MCDM) is one of the several approaches that can be used to solve problems involving a set of alternatives, predefined criteria thereby resulting in the taking the optimal decision or selecting the optimal alternative. It entails a multi-stage or multi-part process involving the definition of objectives, selection of criteria for measuring objectives, specifying alternatives, assigning weights to the criteria, applying the appropriate mathematical algorithm for ranking of alternatives, and selecting the best alternative (Herath and Prato, 2006; Ananda and Herath, 2009; Mosadeghi et al. 2009). MCDM deals with typical real-life problems, especially when dealing with data set with a degree of uncertainty and inaccuracy problems associated with environmental features (Triantaphyllou et al., 1998). BNs are useful multi-criteria decision support tools as it allows the evaluation of changes in outcomes associated with changes in decision influencing variables of the system under consideration or management action.

BNs, (also called belief networks are probabilistic graphical models) can be described as a directed acyclic graph (DAG) comprising of a set of random variables and their conditional dependencies (Nielsen and Jensen 2009). The three main components of a typical BN are: (i) nodes, (ii) directed edges or links between nodes, and (iii) a conditional probability table (CPT). In the DAG, the nodes signify the random variables and the links or directed edges depict the causal relations between these nodes. The causal relations between nodes are described using the CPT. In general, the BN can be defined by a pair A= (U,F) where U is the DAG with nodes $N_1.N_2,N_3,\ldots\ldots,N_n$ representing a set of random variables and F is a set of conditional probability distributions (CPD) associated with U's nodes, and F factorizes according to U, i.e. F can be expressed as a product:

$$F(N_1.N_2,N_3,\ldots\ldots,N_n\ ) = \prod_{i=1}^{n} F\left(N_i \middle| Fa_{N_i}^{U}\right)$$

Where $Fa_{N_i}^{U}$ represents the parent nodes of N_i in graph BN graph 'U'.

If N_i does not have a parent node, it is described by an unconditional probability distribution is said to be unconditional. Conversely, if N_i have a parent node, it is described by a conditional probability distribution. If a variable is represented by a node that cannot be observed, it is said to be latent or hidden while the variable denoted by a node is observed is referred to an evidence node. Figure 3.1: Steps for developing the Bayesian Network Model outlines the steps involved in the construction the BN model.

3.2.1 Define and Specify Overall Model Objectives

The model development starts with a definition of the objective of the model. In cases where diverse stakeholders are involved, the need arises for agreement on the goal of the model, the issues involved and the type of system under consideration. The issues involved or considered will have a significant effect on the development of the model, thereby affecting the management decisions that will be incorporated into the BN.

3.2.2 System Boundaries (Scope and Scale)

It is imperative to take into consideration the temporal and spatial scales relevant to the system under consideration or modelled. Hence, the scope of the system is defined regarding factors that will be considered in the modelling. This creates a clear picture of the system under consideration, its scope, scale and the discrete and factors such environmental conditions (which are variable) and management scenario relevant to the system.

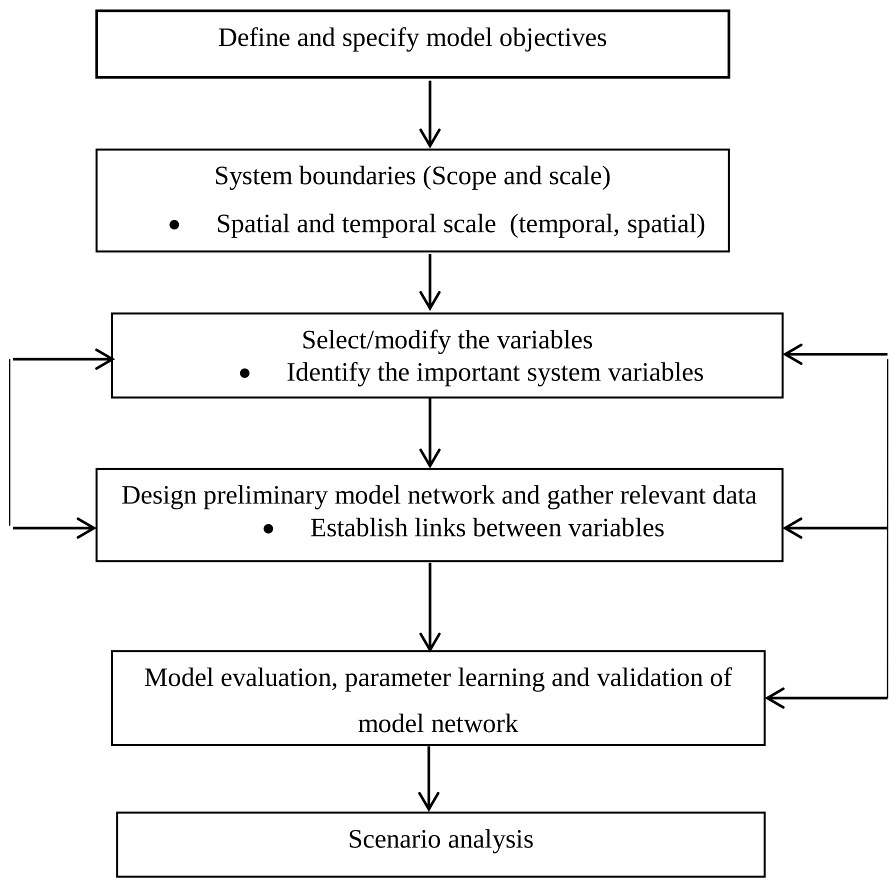


Figure 3.1: Steps for developing the Bayesian Network Model

3.2.3 Select/Modify the Variables

A conceptual BN can be developed when the model's objectives and system boundaries have been established. The preliminary conceptualization entails: (i) identify the critical system variables and (ii) create and establish the links between variables. Typically, there is need to identify variables ('nodes') that are imperative for the system to be modelled. The identification and selection of variables can be based on literature review, consultation with stakeholders and expert opinion. According to Borsuk et al. (2004), the selected variables have to be at least observable or predictable, measurable and should not have an ambiguous definition, e.g., oyster populations can mean oyster size, oyster quality or oyster hatching success. The system variables should be clearly defined to denote what each variable represents and to address the issue of ambiguity. Once the variables are selected, the links between them are identified. The identification of variables and the directed edges transforms to a conceptual BN model depicting the system. The conceptual BN model captures the objective and boundaries of the model, provides a graphical illustration of the system under consideration.

3.2.4 Design Preliminary Model Network and Gather Relevant Data

A pilot network is constructed and links are inserted between variables as well as allocating probabilities and states each variable. The state of each variable represents the potential values or conditions that the variable can assume. States can be of different types such as a probability distribution, an interval, numerical value and categorical definition.

3.2.5 Model evaluation, parameter learning and validation of model network

At this stage, the developed network is evaluated to provide predictions usable return flow from agricultural and domestic activities.

3.2.6 Scenario Analysis

Scenario analysis is an approach for analysing or predicting possible future events taking into consideration alternative possible outcomes. As mentioned earlier, BN is a useful decision support tool as it provides a medium for assessment of relative changes in the outcome probabilities of events associated with changes in system variables, performance parameters and management actions. Hence, by specifying the condition of one or more variables, the bearings on other variables is predictable.

3.3 Materials and Methods

Most of SA's water demand/requirement is met by surface water supplied from rivers and dams. As shown in Figure 3.2, agricultural irrigation account for about 62% of the total water requirement while urban requirements account for about 23%. The other four sectors, namely rural users, mining and bulk industrial, power generation and afforestation share the remaining 15%. Only part of the water used non-consumptively becomes available for re-use. Water abstracted from a surface or groundwater source is said to be consumptively used when it is no longer available for use because it has evaporated, transpired, been incorporated into products and crops, consumed by man or livestock or otherwise removed from freshwater resources.

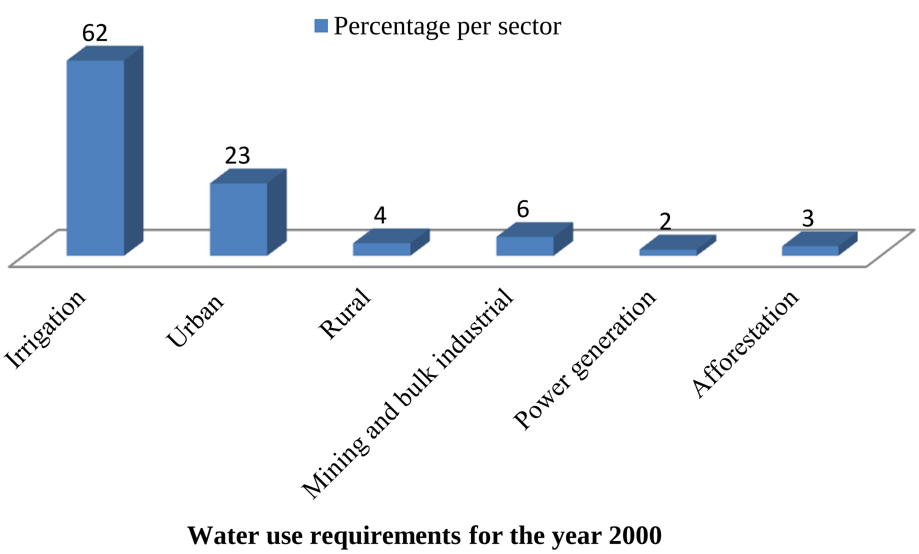


Figure 3.2: Percentage sectorial water requirements in South Africa water sector (adapted from DEAT, 2006)

Complete metabolism of freshwater resources by domestic and agricultural activities has a significant effect on the amount of wastewater generated from both activities that can be recycled and made available for reuse. In this research, we consider the two main types of usable return from agricultural use, urban activities. Water use in the rural areas, as well as for irrigation and thermal power generation, is predominantly consumptive. The non-consumptive water by industrial and domestic activities yields wastewater that serve the purpose of contributing to ecological water reserve and usable return flow. About 20% of runoff is needed to remain in rivers and estuaries to satisfy ecological requirements. Only part of what is left of this wastewater after meeting ecological requirement can be harnessed as usable yield. The reuse of this non-consumptive yield may be further constrained by a variety of pollution sources thereby making it essential to estimate the portion of this yield that available for reuse as shown in Table 3.1.

Table 3.1: Usable return flow by water use sectors of water management areas

Water management areas	Usable return flow (million m^3/annum		
	Irrigation	Urban	Mining and bulk Industrial
Limpopo	8	15	0
Luvuvhu and Letaba	19	4	0
Crocodile West and Marico	44	282	41
Olifants	44	42	14
Inkomati	53	8	11
Total	168	351	66
Percentage (%) return flow	28.7	60	11.3

Adapted from: National Accounts: Environmental Economic Accounts-Water Management Areas in South Africa (2010)

Due to irrigation and domestic (households and urban use) reuse tendencies, factors that stimulate these two types of return flows were considered when developing the models.

3.3.1 Variable description

This section entails the identification and discussion of different variables/factors that influence water supply security and reuse. These variables are useful for efficient management of water resources and imperative for decision making in the BN model development.

- *Water use requirement (WU)*

Water use (WU) requirement is water abstracted from surface and groundwater for agricultural and domestic use to sustain life, industrial and other anthropogenic activities. In SA, WU requirements can be classified into agricultural sectorial WU requirement, urban/domestic sectorial WU requirements, rural WU requirement, power generation WU requirement, afforestation WU requirement and mining and bulk industrial water requirement (DEAT, 2006). These sectorial WU requirements are largely met by surface water supplies from rivers, dams and groundwater (DEAT, 2006). Agricultural water use (AWU) is referred to as water use for irrigation and other agricultural activities in the agriculture sector while domestic water use (DWU) is referred to as water use for domestic activities such cooking, drinking, bathing, laundry and light industrial in the urban sector. Evaluating water requirement use per sector is an intricate task due to the significant variation in water requirements across the country, different sectorial needs regarding quantity, quality, temporal distribution, and assurance of supply (DEAT, 2006). An appropriate understanding of water use requirements per sector is crucial to managing water resources effectively and efficiently.

- *Cost (cost of irrigation water (CIW) and cost of domestic water (CDW)*

According to Biswas and Kirchherr, (2012), the price of water is the most important policy to alter water consumption pattern and users' behaviour. The inverse correlation between water and per capita consumption shows that price could be used to regulate consumption (Almeida 2015). However, there is a minimum consumption that is required without jeopardizing the well-being of the environment and human health. Hence, if CIW and CDW take up a substantial portion of people's income, then alternative sources of water must be found.

- *Standard Precipitation Index (SPI)*

According to Chen et al. (2002), the impacts of climate change include increasing evaporation rates; frequent flooding and drought occurrence; changes in soil moisture; increased runoff; increasing climate variability and changes in water quality and groundwater flow recharge process in shallow aquifers. Drought is brought about by lack or limited rainfall with high temperatures speeding the process of dryness. The Standardized Precipitation Index (SPI) is a tool used by the South Africa Weather Services (SAWS) for measuring the severity of drought based on rainfall data. According to Dai (2011) the increasing trend of persistent drought in arid regions of the globe is a warning signal to the security and reliability of water supply to meet increasing demand, hence the need for alternative water sources.

- *Water Stress Index (WSI)*

Water stress indicator is a function of water availability and water use (Smakhtin, et al. 2005). The WSI depicts the intensity of use of water resources in a region. The WSI value is evaluated by utilizing information about freshwater water availability, total freshwater withdrawals and water availability (which include surface and groundwater.This indicator is defined by the ratio:

$$WSI = \frac{Freshwater\ Withdrawals}{Mean\ annual\ runoff - Ecological\ water\ reserve}$$

- *Population Density (PD)*

Population density is a measurement of population per unit area. Besides climate change, sporadic increase in population growth in major metropolitan areas also increases the vulnerability of access to reliable water supply. In densely populated regions such as Delhi (India), Beijing (China) and Tokyo (Japan), water shortages are becoming more frequent due to water stress intensification and increase in water consumption (Bates et al.2008). In SA, the percentage of the population with access to potable water supply source has risen from 83% in 1990 to 91% in 2008 (Du Plessis 2017). With population on the rise and increasing affluence of the population, water and food consumption trends are like to increase. The increasing population growth rate and growing affluence of the population, explains the rise in water and food consumption trends.

- *Water volume per person per day (WVPP)*

WVPP is the average volume of water used per individual in a day. It provides an indication of the gross volume of water by a person in a day. It is estimated using the equation below:

$$WVPP = \frac{system\ input\ volume\ \times 1000 \div 365}{population}$$

- *Percentage of Non-Revenue water (NRW)*

It refers to all the water that is lost through physical leakage or commercial losses (meter under-registration, billing errors, theft etc.) as well as any unbilled authorized consumption (fire-fighting, mains flushing etc.). NRW is estimated using the equation below:

$$\% \, Non \; Revenue = \frac{system\ input - (billed\ consumption + free\ basic\ water)}{System\ input\ volume} \times 100\%$$

- *Percentage of flushed toilet connected to sewerage (FT)*

This provides an indication of the number of houses within the water management area connected to the sewer system. The more houses connected to the sewer systems the more the volume of wastewater return flow from urban areas.

- *Usable return flow (agricultural and urban)*

Usable return flow refers to wastewater generated from water sectorial activities which can be treated and reused for beneficial purposes. The usable return flow from agricultural water (URFA) refers to the volume of wastewater generated from agricultural activities that can reused for potable/non-potable applications (millions m^3). Usable return flow from urban activities (URFU) refers to volume of wastewater generated from urban/domestic activities that can treated and reused for beneficial purposes (millions $m^{3)}$.

3.3.2 Data description

The data analyzed consists of 82 complete observations. For each sector, the water management areas with no water use in the sector or no usable return flow from the sector were discarded from the analysis. For the prediction of usable return flow from the agricultural sector, the predictor variables considered are WU, AWU, CIW, WSI and SPI. For the prediction of usable return flow from domestic sector, the predictor variables considered are WU, DWU, CDW, WVPP, NRW, FT, WSI and SPI. A partial data set for agricultural sector is shown in the Table 3.2.

Table 3.2: Sample of agricultural sector data (extracted from Appendix 1)

Water management areas sub regions (WMA)	Water use in WMA (Mm^3/y)	Agricultural (AGR) water use in WMA (Mm^3/y)	Water Stress Indicator (WSI)	Standardised Precipitation Index of WMA (Drought)	Share of Usable Return flow from agricultural use (%)
Matlabas/Mokolo	63	48	0.1	0.09	75
Lephalala	42	39	0.3	0.11	0
Mogalakwena	79	56	0.3	-0.26	42.9
Sand	106	69	1.30	-0.21	0
Nzhelele/Nwanedzi	32	26	0.30	-0.07	100
Luvuvhu/Mutale	119	97	0.30	-1	71.4
Shingwedzi	3	0	0.04	-1.83	0
Groot Letaba	174	126	0.50	-1.4	92.9
Klein Letaba	37	25	0.20	-1.27	50
Lower Letaba	0	0	0.04	-1.83	0
Apies/Pienaars	280	41	1.10	-0.14	3.6
Upper Crocodile	556	208	1.50	-3.05	10.8
Elands	113	32	1.00	-0.18	11.1
Lower Crocodile	171	137	0.40	-1.09	60.9

For the agricultural sector, URFA is highly correlated with AWU (0.95) and WU (0.76) (Figure 3.3). The later variables were also highly correlated (0.79). Albeit very low, the correlations of CIW and SPI with WU and AWU and hence with URFA are negative as expected. For the domestic sector, URFU is highly correlated with DWU (0.89) and moderately correlated with WU (0.54) and PD (0.56) (Figure 3.4).

The comprehensive data set of the variables used for the URFA and URFU modelling is presented in Appendix 1 and 2 respectively. The data set used for the estimation of WSI is presented in Appendix 4.

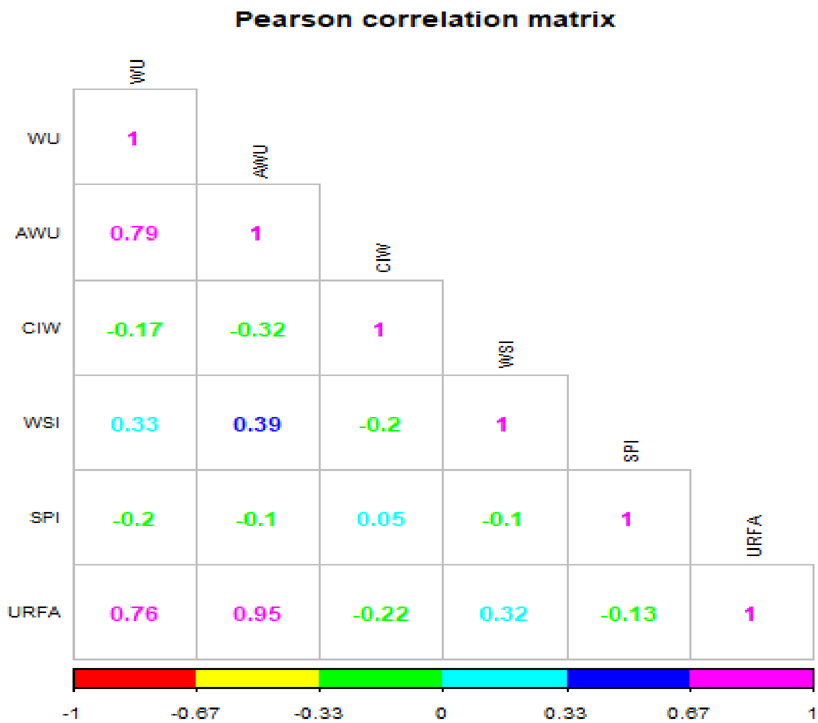


Figure 3.3: Correlation between agricultural (AGR) water reuse features

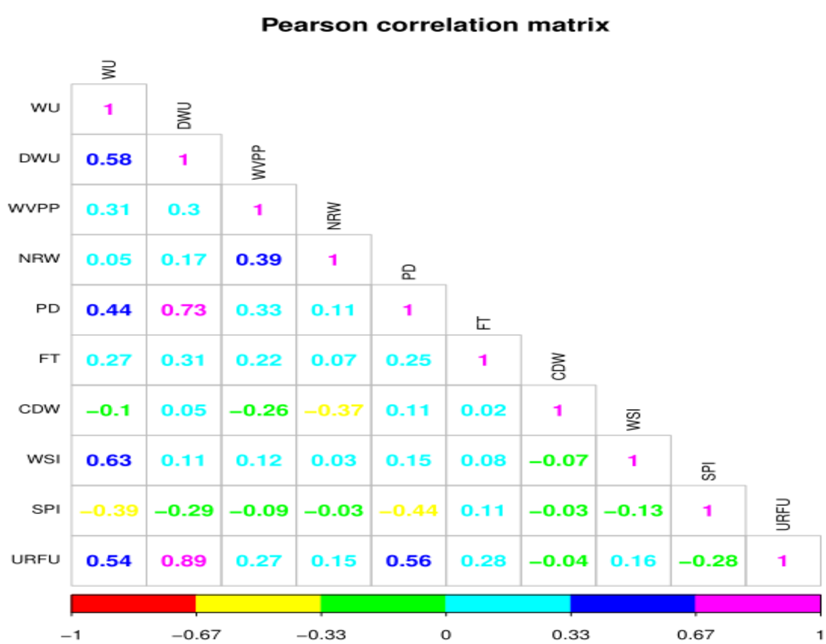


Figure 3.4: Correlation between urban water reuse features

3.4 The Bayesian Network and the linear regression models

For each sector (agricultural and domestic), two models were considered: a linear regression model and a Bayesian networks model.

- Linear regression model: The usable return flow was expressed as a linear function of other variables.
- Bayesian network model: A graphical model for a collection of random variables $N_1, N_2, \dots \dots, N_n$ is a family of probability distributions such that satisfies each a set of conditional independence relations encoded in graph.

This amalgamation of the Probability Theory and Graph Theory provides a parameter parsimonious and modular representation of the joint distribution of the random variables of the model, thereby allowing estimation of model parameters with a reasonable amount of data and a more effective computation of marginal posterior distributions. As stated earlier, Bayesian network is a graphical model wherein the conditional independence relations are encoded in a directed acyclic graph (a graph with orientated edges and such that there are no paths from a node and back).

For the agricultural sector, the graph that represents the dependence between the variables logically was built and the corresponding Gaussian Bayesian network was fitted to the data. For the domestic sector, this study built the graph that represents the dependence structure of the variables from the data using the hill-climbing algorithm (Nagarajan et al, 2013) and the corresponding Gaussian Bayesian network was fitted to the data. In this study, R statistical software (R Core Team, 2017) used for data analysis and the bnlearn package (Scutari, 2009) was used for the Bayesian network modelling.

3.4.1 Models of agriculture water reuse potential

All variables are right skewed and present some outliers. A log transformation of the variables was explored but did not yield better prediction accuracy for both the linear regression model and the Bayesian network model. Instead, it tends to result in considerably underestimating high URFA values. A comparison of Mahalanobis squared distances to the expected chi-square values identified the multivariate outliers as water management areas with very high AWU. A k-means clustering further regrouped most of these outliers along with other observations in a separate cluster. Different models were therefore built for the two clusters.

- ***Linear regression model(URFA)***

The result of the linear regression model is discussed below. The model predications show that AWU have a significant impact on URFA. The fitted linear regression model is described by the equation below:

$$log(1 + URFA) = -1.70402 + 0.85371\ log(1 + AWU)$$

About half of the predictions were more than 28% higher or lower than the actual observation as indicated by the following summary of the distribution of absolute percentage prediction errors:

Table 3.3: Prediction errors of linear regression model (URFA)

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
1.667	18.944	28.167	43.548	57.465	333.536

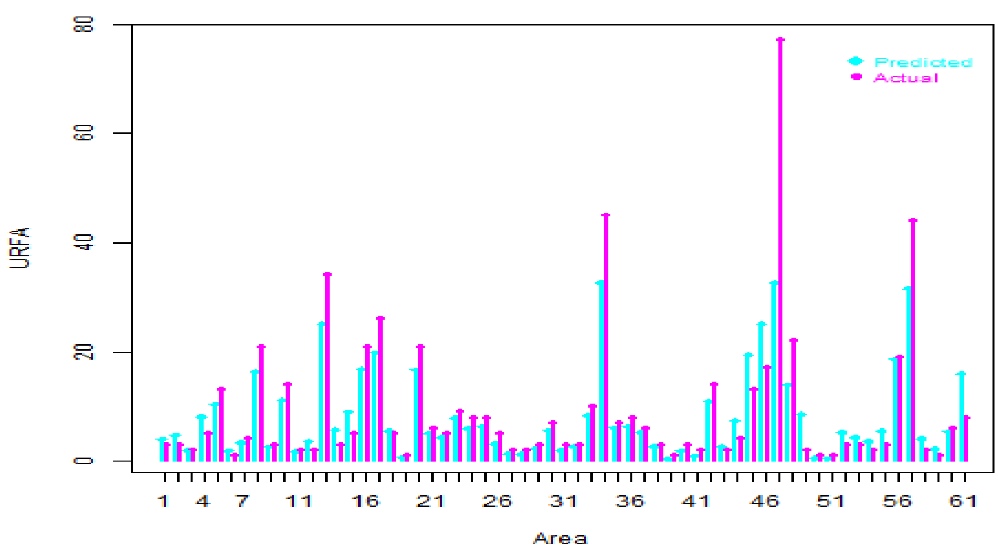


Figure 3.5: Actual vs. Predicted URFA using the linear regression model.

- ***Bayesian network model(URFA)***

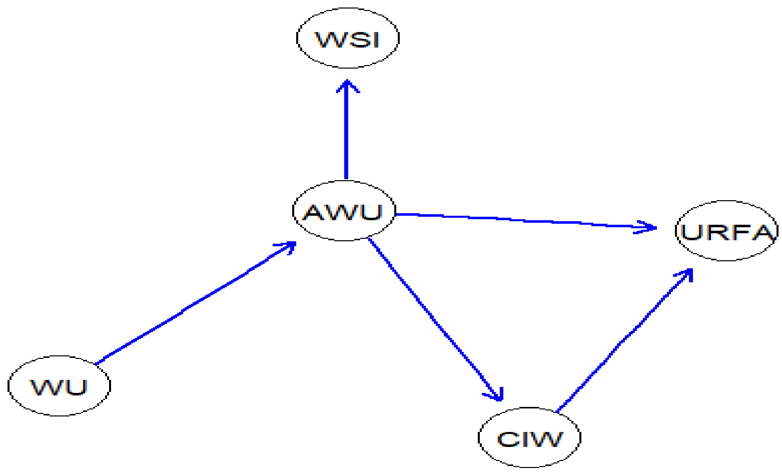


Figure 3.6: Bayesian Network for model representation for usable return flow from agricultural activities

The fitted model parameters for the BN for URFA are shown in Table 3.4 below.

Table 3.4: Fitted model parameters for BN model (URFA)

Parameters of node (Gaussian distribution)	**Conditional density**	**Coefficient**		**Standard deviation of the residuals**
WU	-	Intercept 4.821489	-	0,8312192
AWU	AWU | WU	-0.08428057	WU 0.89057816	0.6146915
CIW	CIW | AWU	(Intercept) 1.32311907	AWU -0.06880547	0.194331
WSI	WSI | AWU	(Intercept) -0.2305150	AWU 0.1319608	0.3724017
URFA	URFA | AWU + CIW	(Intercept) -2.1922928	AWU 0.8790993 CIW 0.3690313	0.3550104

About half of the predictions were more than 25% higher or lower than the actual observation as indicated by the following summary of the distribution of absolute percentage prediction errors (Table 3.5):

Table 3.5: Prediction errors of Bayesian Network model (URFA)

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0.6435	14.4609	25.2957	42.4127	52.3870	333.1310

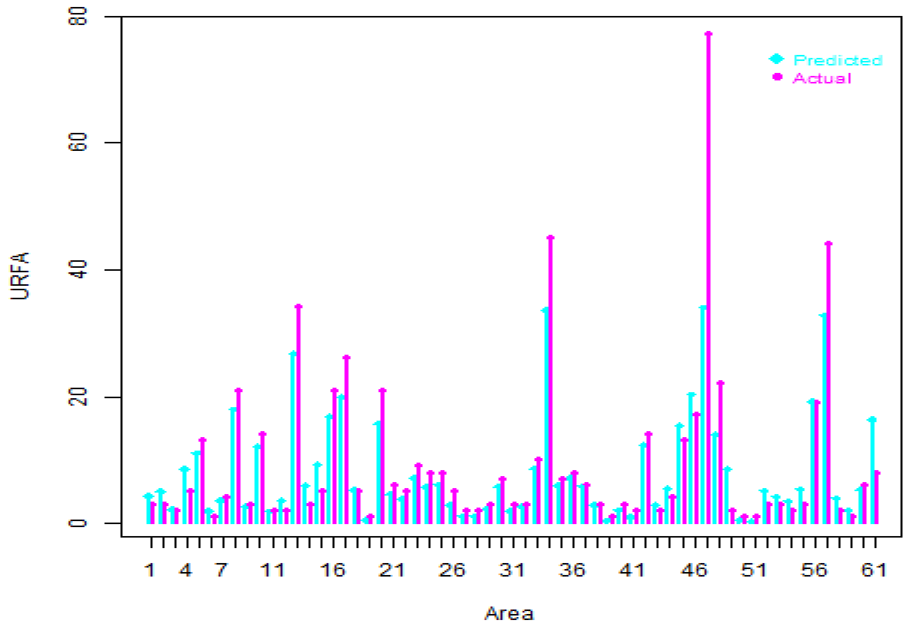


Figure 3.7: Actual vs. Predicted URFA using the Bayesian network model.

3.4.2 Model of urban water usable return flow potential

The following table summarises the distribution of the proportion of domestic water use that is potentially reusable.

- ***Linear regression model (URFU)***

The fitted linear regression model is presented in the equation below:

$$Log\ (1 + URFU) = -0.27349 + 0.68454\ log(1 + DWU) + 0.02924\ log(1 + PD)$$

- ***Performance on modelling data(URFU)***

About half of the predictions were more than 25% higher or lower than the actual observation as indicated by the following summary of the distribution of absolute percentage prediction errors (Table 3.6).

Table 3.6: Prediction errors of linear regression model (URFU)

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
1.191	18.188	25.113	55.495	39.020	784.544

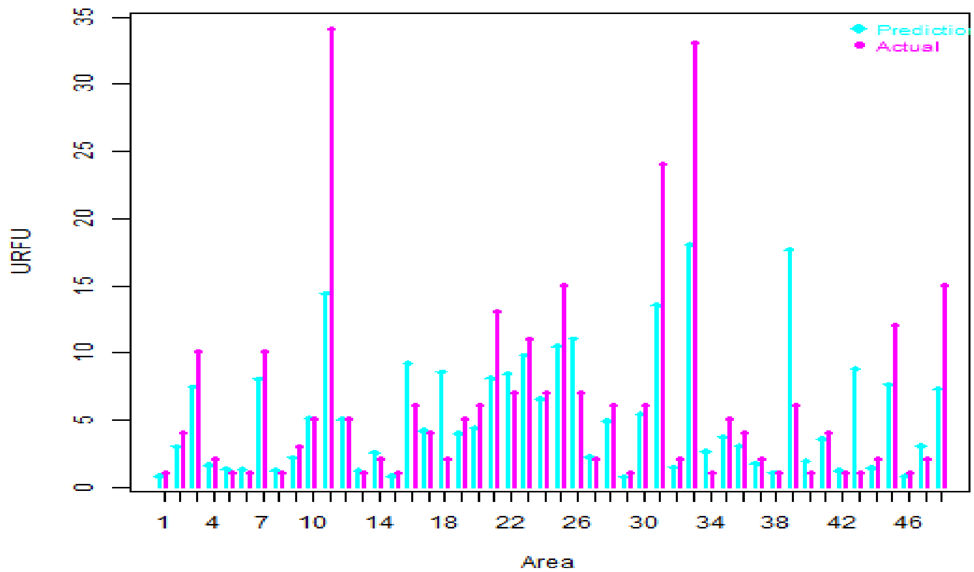


Figure 3.8: Actual vs. Predicted URFU using the linear model

- ***Bayesian network model(URFU)***

The parameters of the fitted Bayesian network model for urban usable return flow are shown in Table 3.7:

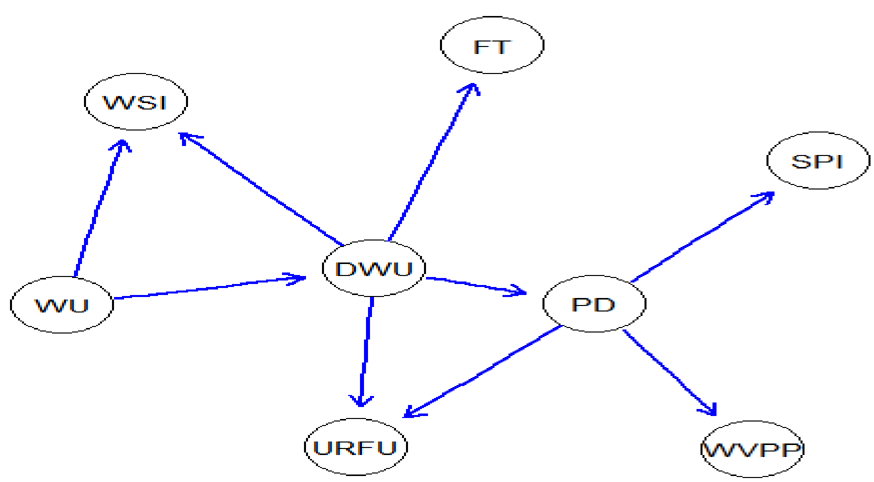


Figure 3.9: Bayesian network representation of factors impacting URFU

Table 3.7: Fitted model parameters for BN model (URFU)

Parameters of node (Gaussian distribution)	Conditional density	Coefficient		Standard deviation of the residuals
WU	WU	(Intercept) 4.671293	-	0.8995938
DWU	DWU | WU	(Intercept) 0.6267200	WU 0.4195331	0.9090694
WVPP	WVPP | PD	(Intercept) 4.83095957	PD 0.05836072	0.7032222
NRW	NRW | WVPP	(Intercept) -0.8925146	WVPP 0.7749754	1.008428
PD	PD | DWU	(Intercept) 1.6611569	DWU 0.7982268	0.9976682
FT	FT | DWU	(Intercept) 3.2937532	DWU 0.2376747	0.6266494
CDW	CDW | NRW	(Intercept) 1.63003126	NRW -0.09651169	0.2717808
WSI	WSI | WU + DWU	(Intercept) -0.31823130	WU 0.15911188 DWU -0.05794291	0.2628787
SPI	SPI | PD	(Intercept) 0.2315174	PD -0.1587085	0.9269126
URFU	URFU | DWU + PD	(Intercept) -0.27348682	DWU 0.68454434 PD 0.02924264	0.4399549

- ***Performance on modelling data(URFU):***

About half of the predictions were more than 25% higher or lower than the actual observation as indicated by the following summary of the distribution of absolute percentage prediction errors (Table 3.8):

Table 3.8: Prediction errors of Bayesian Network model (URFU)

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
1.059	17.471	24.943	55.689	39.372	791.568

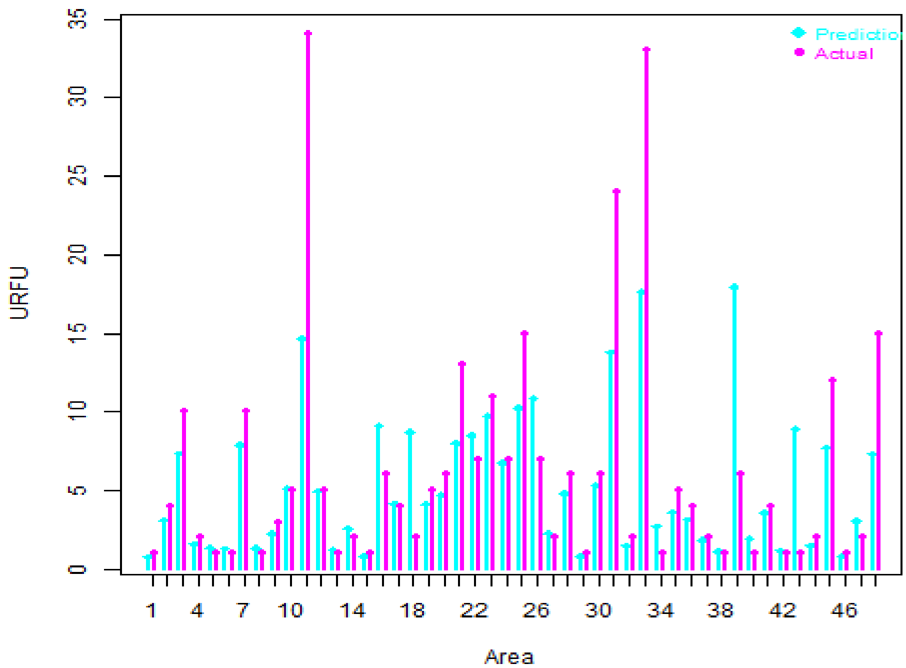


Figure 3:10: Actual vs. Predicted URFU using the Bayesian network model

3.5 Results and discussion

For the agricultural sector, the linear and the Bayesian network models yielded a percentage absolute error of about 28% and 25% respectively. For the domestic sector, the percentage absolute error yielded was about 25%. The predictions are more accurate for the domestic sector. In fact, less than a quarter of the predictions were more than 40% off the actual observations. The performance of the predictions models was certainly affected negatively by the presence of multivariate outliers as indicated by a comparison of squared Mahalanobis distances with corresponding expected chi-square values. This was also indicated by a cluster analysis that put the same areas of water management with very high water use in a separate cluster of few observations. A few extreme outliers were discarded from the analysis. In summary, the study shows that about 8% of the agricultural water use is potentially reusable while about 34% of the total domestic water use is potentially reusable. The study also shows, given the agricultural water use, the usable return flow from agricultural activities can be predicted with a reasonable accuracy. The study also shows that given the domestic water use and the population density, the usable return flow from domestic activities can be predicted with a reasonable accuracy.

3.6 Conclusion

Taking into consideration the several alternative water resources management strategies, the reason to implement any form of reuse must be justified. The first step in the argument to implement reuse is to provide scientific evidence after the fact. Chapter three provides a methodology that is cost effective, accessible and transparent to predict the usable return flow from two main wastewater stream (agricultural and urban (domestic and light industries) sectors in SA. The linear regression model and the Bayesian Network model with reasonable accuracy can predict usable return flow that can be treated and used for other beneficial application. Hence, chapter three provides a foundation on which argument for implementing reuse can be built on before proceeding to the sustainability of the reuse projects.

The development of decision support models that utilizes water and environment related factors to predict usable return flow can be of help to decision makers and facilitate the talks of reuse communities faced with water scarcity. This study suggests that "usable return flow" is an excellent indicator to facilitate decision making with respect to alternative water management strategies such as reuse. Information on usable return flow is imperative to the development and implementation of water reuse initiatives as well as providing warning signals that can predict water supply shortages. The intricacies of the environment outline the factors required to decide the appropriate predicted data. Factors such as water use, sectorial water use, drought, water stress phenomenon, population density, and cost are considered relevant to the apparent necessity for reuse. The models built for agricultural and urban usable return flow predictions takes into account data from 87 regions, in the 19 water management areas in SA. The information provided by the data was valuable in organizing the variables used in the linear regression and BN models. The usable return flow decision influencing variables that resulted from the correlation analysis indicated that AWU and WU are the most representative variables for agricultural usable return flow potential.

On the other hand, it was estimated that DWU, WU and PD are more related to urban usable return flow potential. Other variables, although less representative, allow for model adjustment in order for the data prediction exercise to be carried out. The predicted valves demonstrated the possibilities of identifying the usable return flow through linear regression and BN models. The result of this study also encourage the discussion of challenges facing reliable water supply taking into consideration the effect of climate change scenario.

CHAPTER 4

4 AN INTEGRATED SUSTAINABILITY INDEX FOR ASSESSING SUSTAINABILITY OF WATER REUSE FOR POTABLE APPLICATIONS IN SOUTH AFRICAN COMMUNITIES

4.1 Introduction

The primary aim of this research was to develop an ISI for assessing sustainability of water reuse for potable applications in SA communities. This has been achieved in this study through the development of a framework for identifying criteria that need to be addressed when attempting to achieve the vision of what a sustainable water reuse initiative must be as part of urban water resource management (UWRM) strategy for SA communities. The ISI was applied to a number of case study cities in SA and used to assess some of the potential sustainability attributes that influence water reuse decision making. The results from integrated analysis of criteria as a function of various adapted models, existing performance measurement and regulatory systems brings to focus a broader sustainability assessment process to provide a more detailed analysis which can be used to establish goals and inform strategic processes to enhance the sustainability of reuse for potable applications and its wider uptake. This chapter outlines the general process for the conceptual framework for the development of the ISI.

4.2 Integrated Assessment of Water Reuse Sustainability

Sustainable UWM with a focus on alternative strategies such as reuse, requires well informed decision making based on a comprehensive and holistic assessment of the relevant criteria and indicators. Hence, this requires an integrated approach to link the diverse attributes of sustainability. Parker et. al. (2002) describes the concept of integrated assessment as an emerging discipline with emphasis on the process to bring together diverse and multiple sets of disciplines elements of the decision making challenge through scenario management and stakeholder engagement. The study of integrated sustainability assessment cannot be overemphasized in the development of decision making tools for the water industry. The conventional approach for sustainability assessment of urban water systems (UWS) separately considers 3 items; social, economic and environmental for decision making process. Understanding what a sustainable water system is requires a holistic approach that consolidates the diverse disciplines involved. According to Buselich (2002), there is need for an accurate integrated sustainability assessment approach. Hellstrom et al. (2000) and Connor and Dover (2004), reiterated the fact that sustainability assessment of UWS requires a holistic approach incorporating social, health and technical aspects with environmental and economic aspects for decision making.

Frameworks and sustainability indicators which incorporate criteria can be beneficial in the analysis of UWSs. Ashley et al. (2004) describe a decision making guide for water service providers and this was developed as part of a UK-based research project called: Sustainable Water industry Asset Resource Decisions (SWARD). SWARD categorized the assessment hierarchy by considering the following four categories: economic, environmental, social and technical (which specifically the addresses performance of UWS). The next level down the hierarchy is a number of primary criteria which further cascade down to a larger number of secondary criteria. The bottom level of the hierarchy is the list of indicators or methods of measurement for assessing the performance of UWSs (Figure 4.1).

The Sweden based Urban Water Programme (UWP) describes a set of five primary sustainability criteria: health and hygiene; social and cultural; environmental; economic and technical and functional (Hellstrom et al. 2000, Malmqvist et al. 2006). The primary five criteria described in UWP are in line with the four main categories highlighted by SWARD.As discussed in Lundie et al. (2008), urban water industry needs to develop methodologies for evaluating the sustainability of the various supply and demand options taking into account economic, environmental, human health, technical and social considerations. The UWP criteria may be treated as a water-industry aggrandizement of the triple bottom line attributes of sustainability i.e. social, economic and environment. It is therefore, imperative to consider sustainability attributes such as environmental, social, institutional, technical, and economic in the integrated analysis of UWS. Hence, thinking in terms of only social, economic and environmental is no longer sufficient; technical, institutional and health aspects have to be incorporated into the decision making process as indicated by Hellstrom et. al. (2000), Connor and Dovers (2004) and Lundin et. al.(2006).

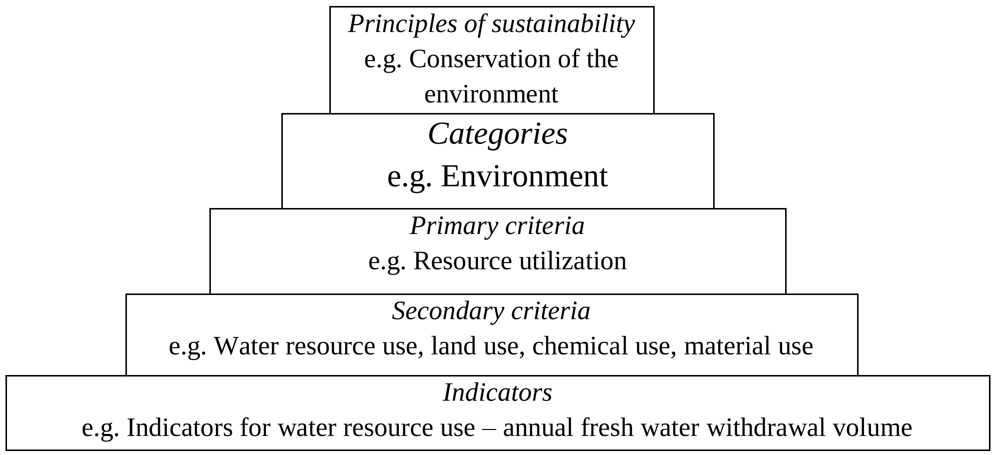


Figure 4.1: Hierarchy of sustainability criteria (Lai et. al. 2008)

The success of alternative water management strategies such as water reuse depend largely on several issues such as water quality and quantity, resources magnitude, cost of infrastructure, environmental impacts and public perception, etc. These issues should be given careful consideration to ensure that water reuse projects are operated and managed in a sustainable ecological environment and in a cost effective manner. This alludes to the importance of the use of criteria that permeates sustainability attributes Figure 4.2 contextualizes the motivation above.

As a comprehensive assessment of these above issues is still lacking in a SA context, this chapter proposes an assessment framework which emphasizes the use of integrated assessment tools such as multi-criteria analysis to evaluate water reuse sustainability for potable applications. According to the NWRS, (2011), plans are underway for development of more water reuse scheme to complement the existing ones. However, this leaves open and calls to question the sustainability of the existing ones. Chapter five presents the outcome of consultation with experts with knowledge on reuse in the water sector in SA to develop criteria that put these issues into perspective for a holistic assessment of water reuse sustainability in a SA context.

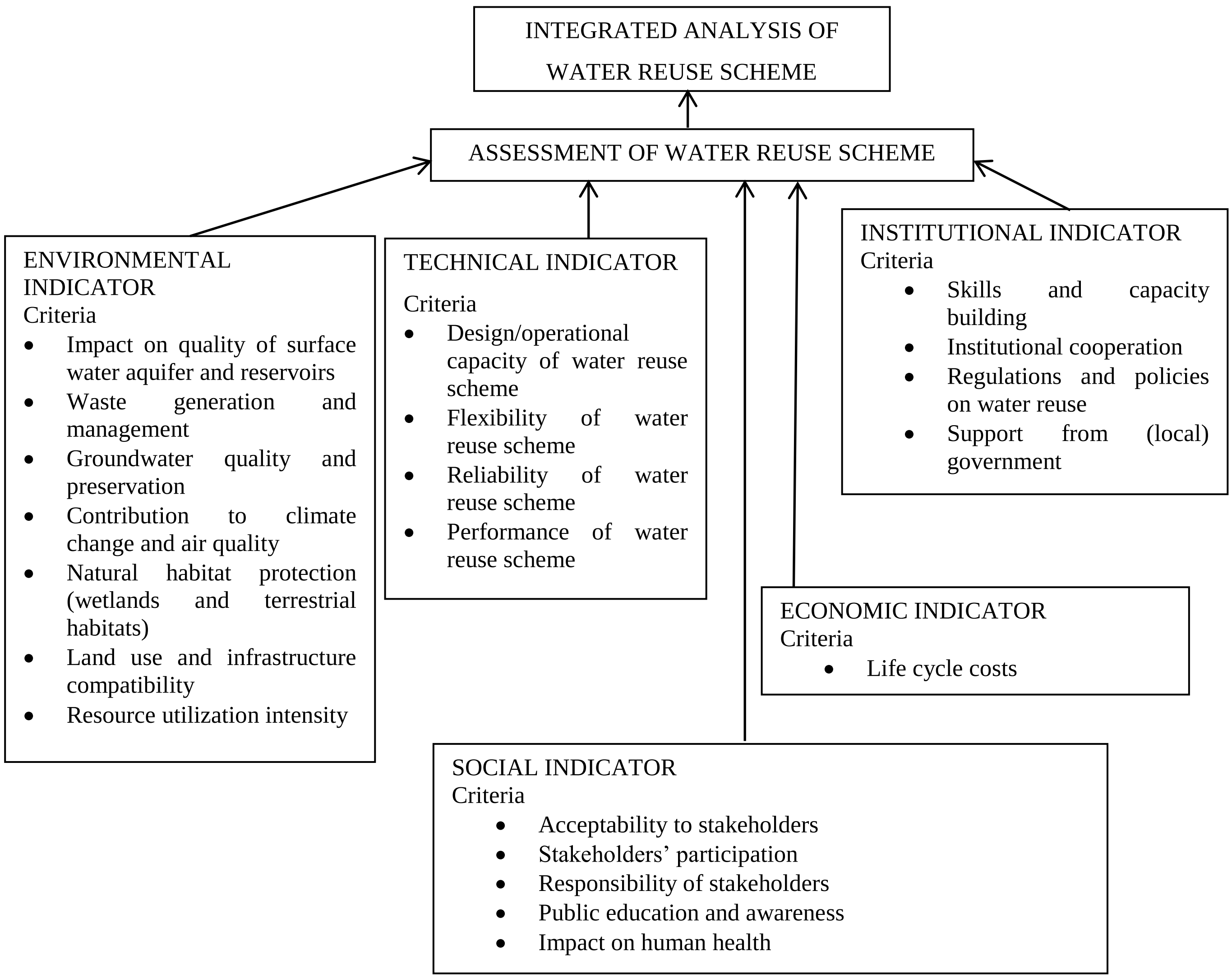


Figure 4.2: Outline of the proposed sustainability performance assessment framework for water reuse schemes

4.3 Sustainability Assessment Framework

SD has become a focal point of discussion at governmental, organizational and system levels in recent years. Several conceptual frameworks that consolidate various disciplines such as economics, engineering and sociology have been developed over the past two decades (Singh et al. 2012). According to Waheed et al., (2009), sustainability assessment frameworks can be classified based on (i) engineering/mathematical techniques; (ii) level of study and (iii) application discipline. Based on literature review (section 2.5.4), this study classified sustainability assessment frameworks into five broad categories namely:

A. Life cycle assessment and material flow analysis (e.g. Lundin 2003, Wernick and Irwin 2005, Malmqvist 2006)
B. Cause and Effect relationship based (e.g. driving force-pressure-state-impact-response (DPSIR), driving force-pressure, state, exposition, effect-action (DPSEEA) and pressure-state-response (PSR), OECD 2003, WWAP 2006)
C. Objectives-oriented (e.g., Pope et al 2004, strategic environmental assessment (SEA) Millennium development goals indicators)
D. Sustainability dimensions/impact driven (e.g., triple-bottom-line assessment (TBL), environmental impact assessment)
E. Process driven or stakeholder participatory approach (e,g, Motevallian and Tabesh 2011)

Each of these frameworks have inadequate capability to address the multi facets issues involved in sustainability assessment holistically and lack the flexibility for usage by several disciplines for a generally accepted interpretation (Waheed et al., 2009). The key characteristics of these frameworks are (1) A clearly defined objectives and assessment criteria that is centered on sustainability dimensions and (2) A definition of measurable indicators set that is relevant to individual assessment criterion. Furthermore, several MCDM methodologies are utilized for aggregation into an index, evaluation of alternatives and stakeholder based assessment process. A sustainability assessment framework helps to clarify the phenomenon to be measured, what to expect from the measuring exercise and the method of measurement used. It should be noted that the function of a framework is to serve as a direct reference to the fundamental SD concepts. At the foundation of any SD framework is a conceptual model that is used for identifying and consolidating the phenomenon that encapsulate what should be evaluated. The major dissimilarities among SD frameworks are reflected in (i) the conceptualization of the main sustainability dimensions in relation to SD; (ii) the interaction and links between the sustainability dimensions considered; (iii) the approach used for grouping phenomenon to be evaluated; and (iv) the justification of the concept used for the selecting evaluating criteria, weighting techniques and aggregation method.

4.4 Proposed Framework for Integrated Sustainability Assessment

According Nardo et al (2008), the development of a framework is critical for creating a platform for selection and amalgamation of criteria into a composite index on the basis of a fit-for-purpose principle. The application of MCDMs in the integrated sustainability assessment process has the potential to help shift UWM towards a more sustainable level. Lai et. al. (2008) defines integrative framework as the problem structuring method which provides guidance for stakeholder engagement, criteria selection and alternative development while integrative tool is the mechanism to combine qualitative and quantitative measures into a single assessment. The various SD frameworks discussed in previous section have their merits and demerits. There is also the possibility of combination of two or more framework together for use. It can be said that no single framework is best ideal to use for SD assessment. For example, the process driven or stakeholder participatory approach based frameworks involve representatives from the community and relevant stakeholders in the planning and developmental process which creates opportunities for educating the public as well as influencing communal behaviors. Sustainability dimensions/impact driven frameworks are majorly useful for assessing the impact of actions/activities on the environment, economy as well as social well-being.

The impacts of these actions/activities are evaluated on the environment based on the system's effectiveness and efficiency. The LCA and MFA are widely used for environmental impact assessment from ‘cradle to the grave”. The causal chain based frameworks employ a variety causal evaluating criteria to identify and assess actions that bring about specific circumstances that affect sustainability, the effects of this cause/action as well as the remedial actions to mitigate the impacts of this cause/action. Pope et al. (2004) indicated that sustainability dimensions/impact driven assessment framework focuses on assessing and mitigating the adverse impacts while the objective oriented framework seek to access the extent to which the implementation of a specific defined outcome. The aim of an EIA-based integrated assessment is to ensure that the triple bottom lines of a proposed action are tolerable in relation to the existing baseline conditions. In contrast is the objectives-led integrated assessment framework that seeks to evaluate the degree to which the implementation of a proposed action contributes towards achieving the defined sustainability vision/goal.

Taking into cognizance all the frameworks discussed, the introduction of the causal chain/linkage based frameworks have proven to be very useful in application to environmental, economic, social context and specific industrial sector. According to Niemeijer and De Groot (2008), the PSR and DPSIR frameworks can clearly illustrate the connection between policy making and overall management. Conversely, the DPSEEA framework further disintegrates the impacts into exposure and effect, in an effort to create a clear path toward the appropriate steps to be taken. Another critical observation with regards to the DPSEEA framework is the close resemblance with the environment and anthropogenic health risk assessment as well as in general risk management frameworks. The causal chain based frameworks have been successful used for sustainability assessment in several disciplines (e.g. health, agricultural and mining sectors). Corvalan et al. (1999), and Khan et al. (2004) emphases the need for the causal chain/linkage based frameworks in combination with other analytical techniques (e.g. LCA, MCDM methods as well as risk assessment methodologies) is essential for a successful and holistic assessment of sustainability. As recommended by Jeon and Amekudzi (2005); Nardo et al. (2008) and Carden (2013), linkage based frameworks can help improve on the existing goals/visions of sustainability through development of policies; monitoring structures aimed at achieving sustainable systems for governmental agencies, corporations and institutions as well as strategic planning techniques and assessment.

The complexity of water reuse schemes as part of alternative water management strategy contributes a major hurdle to difficult task of sustainability assessment as well as the lack of appropriate coordinating medium among multiple disciplines involved. In order to assess the sustainability of reuse for potable application and determine what a sustainable urban water reuse scheme is in the context of UWM in SA, the use of a tool such as a composite sustainability index was explored. Singh et al. (2012) reiterated that the development of composite indicators is considered to be a unique approach for evaluating sustainable development. In this research a conceptual integrative framework for the composite indicator/sustainability index as an integrative tool was iteratively developed to generically define the water reuse system and to identify or verify the different inter- and multi-disciplinary criteria involved. In this study, we propose an integrated causal chain/linkage based for the development of an integrated sustainability index (ISI) to reiterate the need to evaluate specific alternative water management strategy such as reuse.

The causal/linkage based framework has major advantage in sustainability assessment. They provide a platform for clearly structure organization of assessment criteria which is essential for interpretation and dissemination of information to decision makers. These frameworks clearly present information provided by the assessment criteria in relation to several processes, the management actions to be taken and targeted policies seeking to address environment challenges resulting from anthropogenic activities. To establish a comprehensive evaluation system in terms of water reuse sustainability assessment, this study adopted a framework in figure 4.3 based on the steps which have been successfully applied to sustainable development and urban water management (Lundin and Morrison (2002), Lundin et. al. (2006), Mosadeghi et al, (2013) and Carden (2013). The framework proposed in this study was adapted from the study by Carden (2013) on measuring the sustainability of urban water management in SA. However, this framework was limiting in incorporating contribution from stakeholders

and decision makers in the development and selection of criteria used for the assessment process. Input from experts and stakeholders in the criteria selection process will further enhance the robustness of the criteria involved in the assessment process. Motevallian and Tabesh (2011) and Gallego-Ayala et al. (2014) emphasized the need for sustainability assessment framework to incorporate stakeholders and decision makers' participatory approach in the development of sustainability assessment criteria. Hence, this study proposes the framework in figure 4.3 for the assessment of water reuse sustainability for potable applications in SA communities. The proposed framework integrates the stakeholder's participatory approach and DPSEEA frameworks for the sustainability assessment process. Figure 4.3, shows the proposed conceptual integrative framework for the development of the composite indicator by adapting\modifying relevant sections of the above studies. According to the framework below, full assessment procedures in each stage related to water reuse sustainability assessment process recycling schemes can be developed which are summarized below:
Stage 1: After defining the overall research objective, first is to define the specific system and define boundaries for the system under consideration. A desktop study is conducted by collecting and consolidation of available information on gaps and issues affecting the sustainability of water reuse schemes.

Stage 2: Development of assessment criteria from the information gathered and consults experts with knowledge on reuse to select and harmonize assessment criteria and relevance to the spatial/regional context under consideration. These criteria are expected to reflect all the dimension of sustainable toward the goal of achieving a sustainable urban water management resources and development.

Stage 3: Since diverse criteria reflecting the attributes/dimensions of sustainability form the building blocks of the ISI, the evaluation of these criteria will determine the final result of the ISI. Models that depict and quantify these criteria impact will be identified, modified or developed as generic models and employed for this process.

Stage 4: After the development of the ISI, the ISI will be applied to evaluate the sustainability of water reuse for portable applications in selected communities.

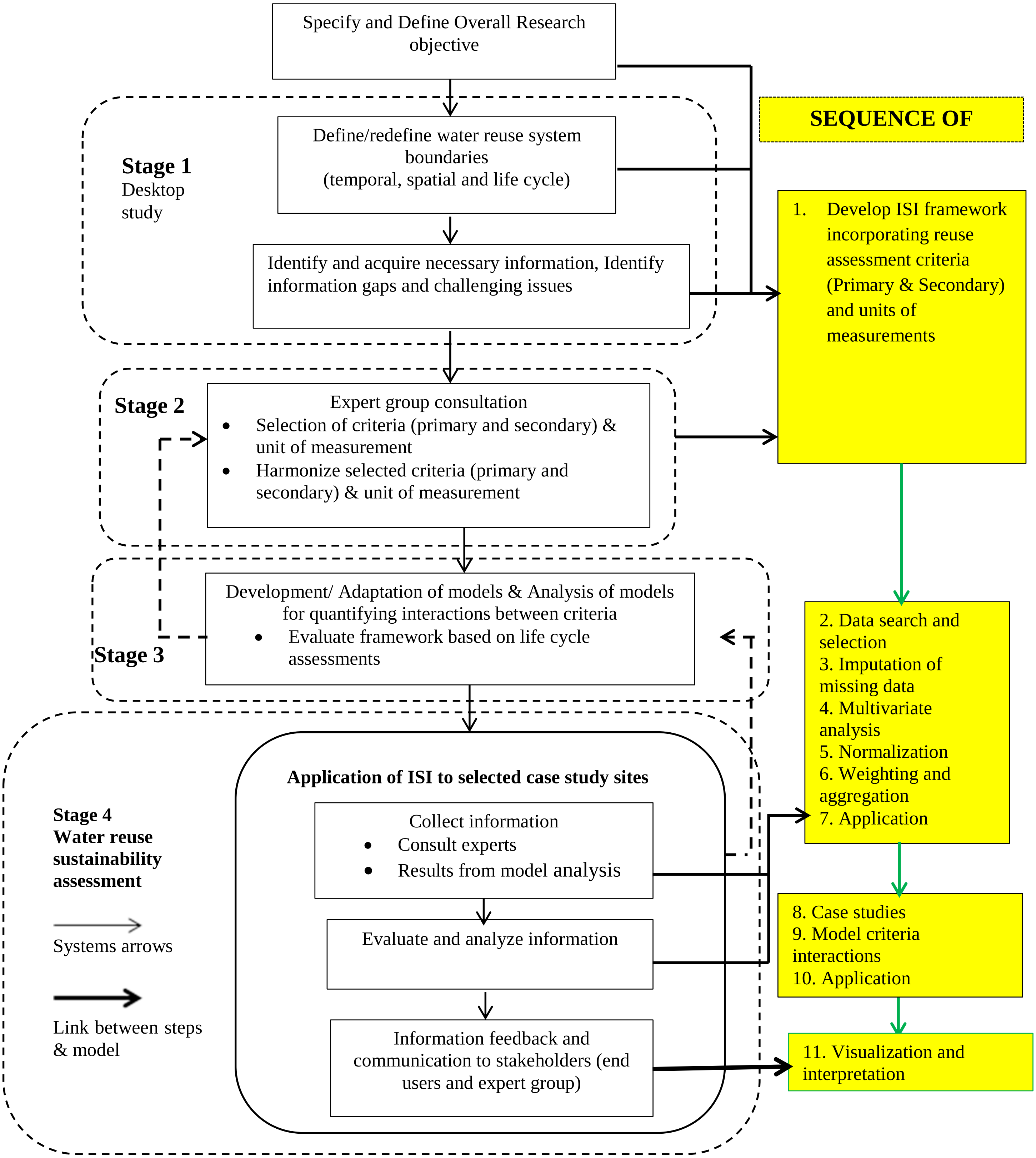


Figure 4.3:Outline of the framework for the integrated sustainability index (Adapted from Carden 2013)

The above framework was adapted from the five-level model coupled with the step-wise methodology proposed by Nardo et al. (2008) and the OECD (2008) methodology for the development of composite indicators as it provides a comprehensive approach for the construction of an index. This was further embellished by considering the classification and evaluation of indicators on the following general dimension of measurement illustrated by Booysen (2002). These general dimensions of measurement include:

- Sustainability aspects to/facets of development be measured by the indicator
- Methods used for the development of the index. For example, does the indicator measure development in a manner that is (i) subjective/objective, (ii) quantitative or quantitative, (iii) cardinal or ordinal, (iv) uni-dimensional or multidimensional
- Whether the index compares the sustainability measure across (i) space ("cross section") or time ("time series") and (ii) in an absolute or relative manner?
- Does the indicator measure sustainability/development in terms of input ("means") or output ("ends")?
- Data availability for the multiple and diverse indicators
- Indicator flexibility to accommodate/allow change, purpose, method and comparative application
- Clarity and simplicity in the content of the indicator, purpose, focus, method, and comparative application

However, the general dimensions for classifying and evaluating sustainability indicators highlighted above are not always mutually exclusive but are often overlap and /or are interdependent. The scale of implementation of the ISI targets national and municipal -level policy with the aim of improving water reuse uptake in the urban sector with respect to informed progress towards sustainability, alignment with existing policies on reuse and highlighting relevant gaps in decision making. The ISI is designed using the five broad components of the sustainability assessment attributes (social, economic, environmental, institutional and technical). This study took into consideration the paradigm shift from a single discipline and sustainability attribute approach and took into account the various significant aspects of systems thinking, as identified by Ravetz (2000):

- Extended time horizons: “linkages within and between generations” - This study primarily seek to assess the sustainability of water reuse schemes which is centered on immediate to short term aspects across five dimensions. Although, it is envisaged that this assessment tool will be able provide a trend in sustainability on long term basis. The longer term assessment of changes can be achieved through application of the ISI on a regular basis (monthly, annually, bi-annually) using relevant data.
- “Extended physical horizons: linkages from local to global” (i.e. spatial characteristics) – It is imperative that a tool of this nature is relevant and readily applicable to different spatial scales (such as municipal, regional, provincial and national spatial scales). Other spatial level taken into consideration are water reuse schemes with respect to scale of reuse such as at micro spatial levels (household, business, or institution), community special level (natural drainage basin) and at river system spatial levels. Although in this study the application of ISI is limited to municipal spatial scale. Efforts will be made to link the ISI to other national and global indicators associated with urban water systems.
- “Extended causal chains: upstream pressures to downstream impacts” – In order to facilitate the better understanding of cause-effect linkage spectrum to an extent, the DSPEEA framework which is a modified DPSIR framework was applied to the urban water reuse scheme in SA. The ISI explores the overall well-being of water reuse schemes as an alternative water management practices as well as an indirect illustration of unsustainable aspects/practices and the possible remedial actions to address them.
- “Extended sectorial boundaries: linkages from environmental to human health perspectives” – As indicated earlier, any form of development will alter the state of the environment. In this study, the ISI indirectly demonstrates the anthropogenic activities that drivers changes to the environmental condition,

exposure effects on health of humans and the environment as well as overall sustainability.

- “Extended value systems: a multiplicity of social, environmental, economic, technical and institutional perspectives” – as far as was possible these linkages were addressed by way of the inclusion in the ISI of all dimensions of sustainability.

This study research took the concept of soft systems thinking approach a step further by the development of a framework for assessing water reuse sustainability which incorporates criteria development and selection using expert opinion with knowledge on reuse. In an effort to create a comprehensive illustration and robust assessment of the various dimensions of sustainability with regards to water reuse sustainability in SA communities.

4.5 Explanation of Sequence of Steps

The construction of the ISI entails selection of various methods/tool/techniques at different stages of development. The explanation of the sequence of steps for the construction of the ISI proceeds as follow as in shown in Figure 4.3

4.5.1 Data Selection and Standardization

The data selection will be based on the analytical soundness, measurability, system boundaries and relevance of the indicators to assessing water reuse sustainability relationship to each other. SA has a fair advantage when it comes to information systems such as Statistics SA. Statistics SA is an equitable sophisticated data system laden with the responsibility of collecting and disseminating (mostly) national data which is complemented by other public and private agencies/establishments that produce and analyze data. The data needed to evaluate the set of criteria that forms the building blocks of the ISI were obtained from official government reports (Statistics SA), published sources, plant information, and interview with relevant stakeholders and surveys. Official technical and statistical bibliographic sources such as Statistics SA and the DWA information portal (i.e. Water Services National Information System (WSNIS: Blue Drop and Green drop scores)) were consulted to extract key data for the calculation of the base criteria. Detailed records of reuse plant performance on operational, services and economic – financial issues were provided by plant operators and technical personnel in charge to highlight performance details needed for evaluating relevant base criteria and to validate developed/adapted models that will quantify the impact of criteria making up the ISI.

4.5.2 Normalization and Standardization

Normalization is used to transform the set of developed criteria which are expressed in different units of measurement into a homogeneous set of criteria expressed in the same unit. The resulting data from the normalization of measured criteria can then be used for comparisons and arithmetic operations. Normalization is required prior to any data aggregation as the indicators in a data set often have different measurement units. The ISI aggregates multiple and different criteria, and it is often the case that these criteria are measured and represented in irreconcilable units. Therefore, it is essential that the data be standardized according to a set and comparable frame of reference. According to Carden (2013), this is necessary in order to eradicate the scale effects of diverse units of measurement without changing the relative distances between observations. A number of normalization methods exist such as ranking, standardization (or Z-scores), Min-Max, distance-to-a-reference and comparison to mean. In this study, the min-max technique was employed for the normalization process. The technique utilizes the maximum and minimum values of a given base to re-scale the base criterion on a defined specific scale range (e.g. 0 (worst possible value) to 5 (best possible value).

In this study, we pre-established a maximum and minimum threshold values for each criterion and allowable range of values, i.e. the minimum allowable value and the best possible value for each criterion. Expert opinions, literature and personal knowledge were used to determine the boundaries of the criteria values in an attempt to balance the distribution between the minimum and maximum threshold values. The mathematical representations of the min-max technique based on the polarity of the criterion are given in equation 4.1 where the higher value of the criterion, the better and equation 4.2, the lower the value of the criterion, the is better.

$$C_n = \frac{C_r - min(C_r)}{max(C_r) - min(C_r)} \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 4.1$$

$$C_n = \frac{max(C_r) - C_r}{max(C_r) - min(C_r)} \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 4.2$$

Where

C_n = normalized value of criterion C

C_r = raw score/value of criterion C (value of criterion C without being normalized)

$max(C_r)$ = maximum raw score/value of criterion C

$minx(C_r)$ = minimum raw score/value of criterion C

4.5.3 Weighting and Aggregation of Component Scores

Weighting and aggregation will be carried out for data set along the lines of the underlying theoretical framework. The analytical hierarchy process (AHP) will be adopted in an attempt to incorporate comments from different sets of stakeholders regarding the choice and prioritization of sustainability indicators and their weight as recommended by Carden et al. (2012). Weighting will be based on stakeholders and expert opinions not technical manipulations to in order to increase the transparency and legitimacy of the ISI. Linear and geometric aggregation methods will be considered in the construction of the composite index with the appropriate method chosen.

4.5.3.1 Weighting

The criterion weighting step seeks to identify the relative importance of the criteria selected as the building blocks of the ISI. Carden (2013) alluded the intricate nature of aggregating information into indices without losing its meaning, importance or becoming too subjective when establishing a weighting system in order to combine the weighted criteria into a single measure. This complexity increases due to the interdisciplinary and multidisciplinary aspects of assessing water reuse sustainability. To aggregate indicators, it is necessary to choose and assign weights which reflect the relative importance of individual indicators to the final composite index. This is why weighting method needs to be made explicit and transparent. Moreover, it should be noted that no matter the weighting systems and methods used, weights are basically value judgments and have the property to make explicit the objectives underlying the construction of a composite index and ensure the results of the evaluation are consistent with the decision makers' preferences. Several decisions have to be made on setting indicator weights/weighting system and the method employed for aggregating component scores into one composite index as it may impact the index value and the resulting ranking. In this study, some base criteria were assigned weights implicitly as well as the introduction and assigning of explicit weights for some base criteria during the scaling process.

4.5.3.2 Aggregation into a Composite Score

Composite indices represent measures arrived at via aggregations of a set of indicators/criteria in an effort to meaningfully synthesis numerous information/factors into one given factor. There are several aggregation techniques in existence and choice of an appropriate technique largely depends on the purpose of the composite indicator and the aspect or facets of sustainable development being measure (Yale, 2005). The aggregation of indices tends to be of either additive or functional in nature. The aggregation technique which is functional in nature is based on functional relationship between specific variables whereas additive in nature entails the simple addition of component scores to arrive at index value. In practice, the selection of aggregation methodology (weighted sum, in the form of an average) or additive (weighted geometric mean) is another controversial aspect in the construction of a composite indicator (Bohringer and Jochem, 2007; Gallego-Ayala et. al., 2014). Geometric aggregation approach is appropriate for use in cases where non-equivalent sub-criteria are positive and expressed in different ratio-scales while linear aggregation method is suitable for in cases where the sub-criteria have the same unit of measurement and additional ambiguities due to the effects of scale have been nullified. Linear aggregation is expressed by equation 4.5, while geometric aggregation is expressed by equation 4.6.

$$I_i = \sum_{i=1}^{N} W_{c,i} NC_i \dots \dots \dots \dots \dots \dots \dots \dots \; equation\ 4.5$$

Where

$i =$ is the specific system under consideration

$W_{c,i}$ = assigned weight of criteria C

NC_i = normalized value of criteria C

$$I_i = \prod_{k=1}^{n} (w_k C_k)^{\frac{1}{n}} \dots\dots\dots\dots\dots\dots\dots\dots \text{ equation } 4.6$$

$$i = 1, \cdots, n$$

Where

I_i = is geometric mean of criteria data set , $(C_1, C_2, C_3, \cdots, C_n)$

w_k = is the k^{th} weight assigned to criterion C_k

C_k = is the specific criteria used to construct the index

In this study, we assume a degree of compensation among criteria. Hence, the result and the conclusions obtained from the ISI could be influenced by the aggregation method employed. Taking into consideration this limitation, this study seeks to obtain a more consistent result by employing the use of the linear and geometric aggregation methods to allow various degree of compensation among criteria.

4.5.4 Sensitivity Analysis

Sensitivity analysis was undertaken to assist in identifying the gaps and assess the robustness of the indicator in terms of e.g., the mechanism for including or excluding an indicator, the normalization scheme, the imputation of missing data, the choice of weights and aggregation method to further enhance the transparency and credibility of the composite indicator.

4.6 Computing the sustainability of water reuse for potable applications

The water reuse sustainability index/composite indicator will be constructed as an interactive soft computing-based program, using a multi-criteria analysis approach, which would allow for the attribution of different weights as well as the aggregation of the different criteria into a single figure result.

4.7 Visualization and Interpretation of Index

For the sustainability assessment exercise, the interpretation of the ISI scores and dissemination of the results is very crucial particularly in terms of promoting sustainability from an abstract context to a more practical and operational context. Furthermore, another important aspect to take into account is benchmarking the ISI results against other sustainability assessment initiatives in order to verify targets for sustainability and provision of a means of interpreting the results. It should be noted that, as with any similar quantitative approach to what is essentially an objective and reflective exercise, there is tendency for some subjectivity with the results of the case study site sustainability assessment. The possibility of data manipulation is inherent for the numerical ranges for the criteria (primary and secondary); score rating of scores; as well as in the way in which the index calculation is done. However, one of the ways employed for reducing the subjectivity of the index is by the use of published data sets and representative models for the developed criteria (primary and secondary) which is further bolstered by exploring its relevancy and associativity to existing regulatory measurement and assessment processes for water resources management at catchment or national levels. In an effort to tackle the criticism of sustainability assessment exercise of being somewhat arbitrary in nature, the index contributes by providing a platform for practical and operational sustainability assessment exercises which should not be a once off exercise but a regular process which can be annual or bi-annual from which trends and time series information can be deduced.

4.8 Summary

This section outlined the process followed in developing the ISI and also provided specific details on its calculation. Through the framework that was adopted, the ISI shows how indicators can be used to provide an analysis of whether an urban water reuse system is moving towards or away from a sustainable state. As will be discussed in more details in Chapter 5, the various recommendations and conclusions arising from the consultation with water experts with knowledge on reuse in the water sector which was used for the final selection of criteria (primary and secondary) constituting the ISI. Potential data sources for analyzing the developed/adapted models for criteria evaluation were identified, as well as the finalization of the aggregation procedures for the final composite score. Consultation and engagement with the relevant local authority officials and stakeholders was an ongoing activity that spanned throughout the development, application and dissemination of the results of the ISI. Once the ISI is finalized, it was applied to the cities where reuse is developed to augment water supply provision in an attempt to assess water reuse sustainability in these areas, and to further validate the ISI. The ISI brings to focus the strengths and weaknesses in the management of water reuse initiatives for potable application in the catchment areas where reuse is developed and communities where reuse initiatives is developing and consequently in the performance across each dimension/aspect/attribute of sustainability (social, environmental, economic, technical and institutional), drawing attention to specific challenges through interrogation and assessment of the individual sustainability aspect and representative criterion results.

CHAPTER 5

5 DEVELOPMENT OF CRITERIA FOR ASSESSING SUSTAINABILITY OF WATER REUSE FOR POTABLE APPLICATIONS IN SOUTH AFRICAN COMMUNITIES

5.1 Introduction

The extent of water reuse in SA is very likely to increase substantially over time. There is therefore need for monitoring and information tools to assess the quantity, quality, use and sustainability aspects of water reuse at catchment and national levels, as well as compliance with resource quality objectives, health of aquatic ecosystems and atmospheric conditions. One method of fulfilling some of these requirements is through the development and use of suitable sustainable criteria (quantitative and qualitative) that provide a means of assessing and communicating information about progress towards reuse goals in a significant and simplified manner. This chapter presents the outcome of consultation with experts in the SA with knowledge on reuse to develop criteria for a holistic assessment of water reuse sustainability in South African communities.

5.2 Background to Study

In assessing sustainable development processes, e.g. IWRM, criteria and indicators can be used to demonstrate the changes in aspects of sustainability (social, economic, technical, environmental and institutional) as a result of implementing policies, projects, plans and programs. Foxon et al. (2002) defined 'criteria' as the set of factors that may be used to make a judgment about the relative sustainability of a set of options and 'indicators' as measures of past and current values of specific criteria which can be used as baseline for future performances. Currently there is no tool to assess the sustainability of urban water reuse schemes in SA. The Organization for Economic Co-operation and Development (OECD), United Nations (UN), United States Environmental Protection Agency (USEPA), and the European Environment Agency (EEA) have developed templates of different sets of core criteria and indicators which are measurable aspects of the environment/society/project/system that can be used to monitor its progress/direction in relevant spatial contexts. A significant number of studies have utilized these set of core criteria and indicators to assess the performance of systems associated with the water industry of different regions across the world. It must be noted that most criteria and indicators are developed in relation to the system under consideration.

Criteria and indicators must provide appropriate and reasonable information to enable the goals and objectives, of the sustainable development assessment, to be addressed. Furthermore, Cloquell-Ballester et al. (2006) suggests the indicators should be validated and accepted beforehand by decision makers and stakeholders of any assessment process. One major function of an indicator is to reduce the complexity and volume of information which is required by stakeholders and decision makers. Several studies on sustainable development and IWRM have used approaches such as social survey in form of research questionnaires, workshops, seminars, expert panels, oral interviews, formal meetings and site visits to develop criteria and associated units/methods of measurement. Gallego-Ayala et al. (2014) used an expert panel comprising of technicians from the Water Regulatory Council of Mozambique and the main water supply institutions in Mozambique to debate and harmonize aspects such as selecting base indicators, indicator weights and indicator boundaries involved in the construction of a water utility performance index (WUPI). This was achieved using an interactive approach by the means of a round table meeting to agree on the criteria and indicators constituting the WUPI. Carden (2013) developed a set of indicators (Sustainability Index) to assess urban water management in South Africa. A participatory process involving the use of oral interviews with municipal officials, local authorities and other stakeholders; assessment of data availability and data credibility; and review of existing indices to identify suitable indicators and variables; was used to develop a comprehensive list of indicators to assess the sustainability of urban water management in SA.

A study by Upadhyaya and Moore (2012) utilized an interactive approach in the form of formal and informal meetings with stakeholders from the rural water authority, reviewing and examining issues related to reuse, and Australian policy and guidelines on sustainability to develop a set of sustainability indicators for assessing the sustainability performance of reuse systems in Australia. Donnelly et al. (2007) demonstrated the effectiveness of a workshop based approach to develop suitable criteria for selecting environmental indicators for use in strategic environmental assessment (SEA). A multidisciplinary team of 28 delegates which consisted of representatives from each of four environmental sectors i.e. biodiversity, air, climate and water, with strategic environmental assessment experts, planning experts, academics and consultants were used in this study. The team's task was to determine the optimum set of environmental indicators for a particular SEA which will lead to an efficient monitoring program, reduced costs and maximized use of resources. Moreover, Neba et al. (2007) suggest that both selection of criteria and indicators differ between developed and developing countries largely as a result of the needs and prevailing socio-economic conditions in different regions. The local conditions in the selected case study sites to be assessed therefore will inform the choice of indicators based on the main purpose of the system in question. This alludes to the importance of developing these criteria taking into consideration environmental, economic, social, institutional and regulatory impediments/factors that suit a South African reuse schemes to provide a holistic approach to assess the sustainability of urban water reuse schemes (Figure 4.1 contextualizes the motivation above).

5.3 Methodology

The types of possible water reuse schemes in SA were considered, stakeholders identified and impediments to water reuse as well as legislation and regulatory requirements were studied. An extensive literature review of sustainability and IWRM related journal articles, conference papers, reports and thesis (such as Hellstrom et al.2000; Lazarova et al 2001; Foxon et al. 2002, Menegaki et al. 2007; Makropoulos et al. 2008; Ilemobade et al. 2009; Adewumi et al. 2010; NWRS, 2011; Leverenz et al. 2011; Upadhyaya and Moore, 2012; Ilemobade et al 2012; Chen et al.2013) was carried out to understand the concept of sustainability in terms of water reuse schemes. Existing sustainability criteria and indicators were reviewed. The five key considerations which are (i) water quality and security of supply; (ii) water treatment technology; (iii) Cost relative to other water supply alternatives; (iv) Social and cultural perceptions and (v) Environmental considerations; that affect choices related to water reuse as an option for water supply and augmentation put forward by to the South African's NWRS, (2011) were reviewed and analyzed. Hence, it became imperative to develop criteria specifically for sustainability assessment process of water reuse schemes which will be accompanied by methods of measurement to ensure that the criteria are fit for the purpose which they are intended for. The study was conducted using the framework shown in Figure 5.1.

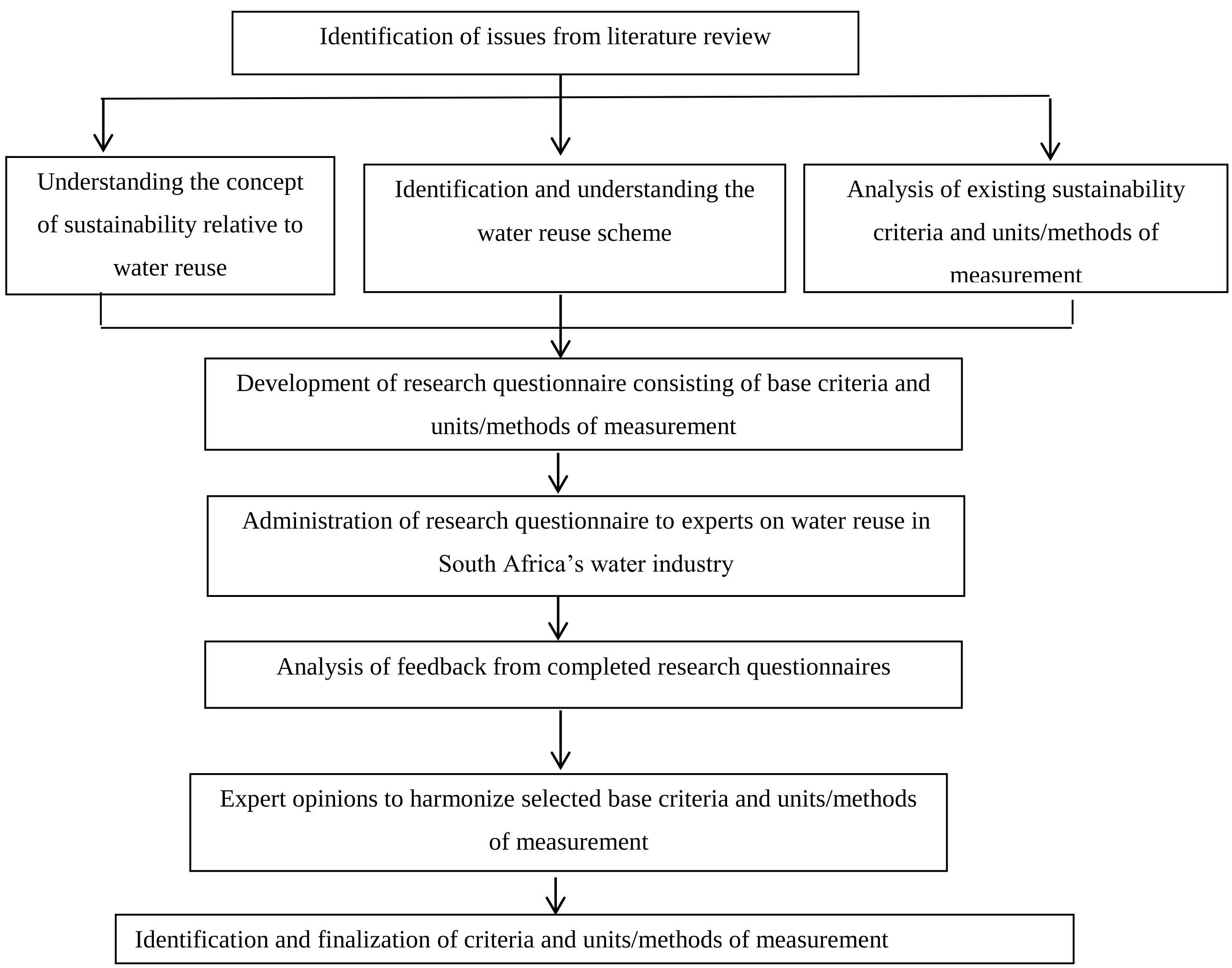


Figure 5.1: Framework for development of criteria for holistic assessment of water reuse sustainability

A questionnaire was developed as a tool for identifying criteria (primary and secondary) and methods of measurement. The criteria and associated methods of measurement developed were subjected to the 3S validation process proposed by Cloquell-Ballester et al. (2006). Cloquell-Ballester et al. (2006) suggested three forms of validation which are (i) self-validation; (ii) scientific validation; and (iii) social validation. The criteria and associated methods of measurement selected were validated by the water reuse experts i.e. self-validation, that participated in the study, to ensure appropriateness to the objective of the study. Scientific validation was carried out and ensured by the appraisal of criteria and associated methods of measurement from case studies and expert opinions. The social validation was ensured by participation of different stakeholders with knowledge of water reuse across the water industry in SA which ensured the information provided was understandable.

These criteria (primary and secondary) are expected to reflect a variety of sustainability issues associated with water reuse schemes, tract/predict changes, identify stressors/stressed systems and influence decision making. A social survey in the form of a research questionnaire was developed, administered and analyzed to extract expert opinions and insight necessary for the development of criteria and indicators imperative for assessing the sustainability of urban water reuse schemes in SA for potable applications. An appraisal of the developed criteria (i.e. primary and secondary) and associated methods of measurement is required to determine their relevancy to the SA context and possible recommendations. This method of developing, administering and analyzing questionnaires was adopted in this study based on its use in several studies on IWRM such as Po et al. (2003); Po et al. (2005); Menegaki et al. (2007); Ilemobade et al. (2008); Olanrewaju et al. (2010) and Adewumi et al. (2011).

5.4 Development of Criteria from Identification of Issues Regarding Water Reuse Sustainability for Potable Applications

5.4.1 Environmental Aspect of Water Reuse Sustainability

Urban water reuse schemes have a significant and long term impact on land, natural water resources, energy, the environment receiving recycled/reclaimed water, by-products from reclamation/recycling processes, pollutants, emissions, etc. (Listowski et al. 2009). The broad principles under which the basic environmental criteria for water reuse can be summarized include:

- Conservation of resources, e.g. natural water resources (surface and ground water) and energy (electricity, fossil fuel and chemicals).
- Reduction in pollution of receiving water bodies e.g. blooms of cyanobacteria/algae and excessive growth of macrophytes. This brings to focus the nutrient removal capability of water reuse systems. Eutrophication potential describes the nutrient discharge in connection with full life cycle of water servicing and reuse options (Schulz et al.2011).
- Reduction of adverse environmental impact and potential risk to the environment, e.g. green-house gas (GHG) emissions, sludge and brine as bye-product from treatment processes of water reuse system.

Many studies on IWRM focus on reducing water consumption relative to demand based on the assumption that environmental impacts can be minimized through efficient water usage. The question of IWRM and environmental impact associated with implementation and sustainability of urban water reuse schemes will be addressed in this study. The important challenge is demonstrating that there should be a balance and tangible offsets between competing sustainability objectives thereby creating a positive outcome. Therefore, water reuse must be evaluated within context of other water supply and augmentation options when considering environmental impacts, energy usage, as well as carbon and ecological footprint.

5.4.2 Economic Aspect of Water Reuse Sustainability

It is vital to carry out a thorough performance and cost analysis which is crucial for the successful implementation and continued operation of a water reuse scheme. Hernandez et al. (2006) suggested that the economic aspect is the best way to realistically analyze, compare and to determine the water reuse scheme that would provide required levels of treatment and desired reclaimed/recycled water quality at unit cost from a selection of combinations of technologies and treatment processes. Economic analysis should take into consideration the capital expenditure, annual energy cost –related operating expenditure and other operating expenditures such as maintenance cost and cost of unplanned maintenance (i.e. pump replacement, filters etc.) through the design life of the water reuse system. Whether reclaimed is used is for a potable or non-potable applications, the cost of a water reuse scheme is strongly affected factors such as location of a reclaimed water source (i.e. the wastewater treatment facility), water reclamation treatment infrastructure, plant influent water quality, customer use requirements, transmission and pumping, timing and storage needs, energy requirements, concentrate disposal and financing costs. The local constraints that can affect cost of water reuse scheme include cost of land for building, distance between production site and consumers and the need to install a dual reticulation system of retrofitting.

A water reuse project generates both monetary and non-monetary benefits. As a result, water reuse projects are often undervalued in comparison to other projects; significant opportunities for beneficial reuse are lost in this way (Sheikh et al., 1998). The non-monetary benefits of water reuse schemes include (i) improved environmental quality and public health; (ii) reduced discharge of nutrients into receiving water; (iii) lower drinking water treatment costs; (iv) conservation of recreational land use and (v) tourism (Lazarova et al. 2001). Water reuse schemes are also typical beneficial to the wastewater agency and local authorities. These benefits include (i) reduced effluent discharge and preservation of discharge capacity, (ii) elimination of some treatment processes to meet mass limits, i.e. for nutrients, (iii) reduction or elimination of major sewers owing to construction of satellite water reclamation plants, and (iv) cost of reclaimed water.

5.4.3 Social Aspect of Water Reuse Sustainability

According to Stenekes et al. (2006) and Khan and Gerrard (2006), the central role played by community acceptance is evident in failures of numerous water recycling schemes. For sustainable development of water reuse schemes, an understanding of the cultural and social aspects of water reuse is essential (Lazarova et. al. 2001). Water reuse projects are susceptible to failure due to lack of social/public support and reuse for potable applications is often met with strong opposition even in developed countries. Even for non-potable applications, public attitudes such as perceptions of water quality, trust in water authority and service providers, willingness to pay and use or accept water reuse project play an important part. Other key factors to the success of water reuse projects in every community are the public's knowledge and understanding of safety and application of reclaimed/recycled water. As well as the challenge of local skills and capacities to utilize the treatment technology and public perception of risk or acceptability are crucial.

In the last decade there have increasing number of bodies of research investigating community attitudes and acceptance of reclaimed/recycled water schemes in a bid to ensure successful implementation and sustainability (Chen et al., 2013; Ilemobade et al., 2012; Ward et al., 2012; Adewumi et al 2010; Alves et al., 2011, Hurlimann et al. 2008; Hurlimann, 2007; Nancarrow et al., 2009; Hurlimann and McKay, 2006; Leviston et al., 2006; Marks et al, 2006a; Marks et al.,2006b; Po et al., 2005; Marks, 2004; Po et al., 2004). The study by Muanda et al. (2017) was part of the effort by the Water Research Commission (WRC) to investigate institutional and social factors influencing public acceptance of reclaimed water for potable uses in Beaufort-West, eThekwini, and Overstrand municipalities in SA. The implementation of water reuse schemes especially in SA faces a number of social impediments such as (i) the poor communication of information among parties involved; (ii) perceived risk to health and hygiene; (iii) perceived impact on the environment due to reuse; (iv) social equity; (v) religious and cultural beliefs; and (vi) trust in technology, water authorities and service providers. In order to protect the environment and public health, it is important to put into perspective specific factors that could potentially influence public perceptions and acceptance of reclaimed/recycled water use. These include the following:

- Effluent sources
- Constituents of concern in effluent
- Treatment technology,
- Reclaimed/recycled water quality standards,

- Health risk and exposure
- Environmental impact
- Economic drivers and cost benefits,
- Operations, management and adequate contingency plans and provisions
- Institutional cooperation

Therefore, it can be deduced that water reuse projects as an alternative water supply source to meet growing demand should have at its core balancing the protection of public health without putting unnecessary strain on the environment and the implications of other sustainability aspects. It is important to note that even those water reuse schemes whose products are not directly used for human consumption can impact the management of the overall urban water cycle. For example, re-using water with high salt concentrations for irrigation purposes could potentially impact the quality of water bodies within a given watershed. This impact (on natural water bodies) will have an effect at treatment plants that source their water from the same watershed. Treating such an effluent to drinking water standards could still be achieved but the cost of doing so (treatment technology) could be significantly higher than what it would cost to treat water with lower salt concentrations. As illustrated above, water reuse schemes need to be imagined as part of a broader narrative for managing water resources which cannot be isolated from other segments of the natural water cycle and achieving the goal of a sustainable environment and society.

5.4.4 Technical Aspect of Water Reuse Sustainability

With the available technologies, any water quality required by users and for compliance with existing regulations can be achieved. Extensive or intensive technologies can be applied, depending on local conditions, intended use of the water, plant size and water quality standards (Lazarova et al. 1998). Treatment processes in wastewater reclamation plants are employed either individually or in combination to achieve the required reclaimed water quality. Considering the main unit processes and operations commonly used in water reclamation, quite a number of treatment process flow arrangements can be developed to meet the water quality requirements of a certain reuse application. Key factors that may affect the choice of water reclamation technology include (i) the type of water reuse application; (ii) reclaimed water quality objectives; (iii) the wastewater characteristics of the source water; (iv) compatibility with existing conditions; (v) process flexibility; (vi) operating and maintenance requirements; (vii) energy and chemical requirements; (viii) personnel and staffing requirements, (ix) residual disposal options and (x) environmental constraints (Asano et al., 2007). Decisions on treatment design are also often influenced by water rights, economics, institutional issues, and public confidence. The relative importance of some of these factors is likely to change over time to ensure the continuous operation and sustainability of water reclamation projects. With the push towards a low-carbon society to limit greenhouse gas emissions and introduction of carbon taxes in some regions across the globe, energy-intense treatment processes are becoming less favorable.

One of the main technical challenges to the sustainability of water reuse systems is how to achieve a high level of operational reliability, not only of treatment facilities but also of storage reservoirs and reticulation networks. Each water reuse schemes still require a thorough site-specific assessment, general standards operating and maintenance procedures as well as appropriate monitoring approaches to foster wider application and sustainability. Different water service authorities have different operation maintenance procedures and water quality guidelines for potable water and the various classes of reclaimed water. In SA, drinking water quality must meet the South African's water quality national guidelines (which is under review), as well as the SANS 241 standard for potable water. It is imperative for the reuse system to satisfy these guidelines. The degree of treatment is basically influenced by the type of reuse. If the reuse is for potable application, the reclaimed water will be of high quality. However, a threshold value can be assigned for the quality of reclaimed water. Hence if the quality of reclaimed water is up to the required standard, the reuse system is considered sustainable. The treatment level below or above the required level is generally being termed as improper use and can both be considered as unsustainable. The treatment above required level may require an advanced treatment technology requiring more resources and energy, which in turn can increase cost and GHG emissions respectively.

5.4.5 Institutional Aspect of Water Reuse Sustainability

Institutional aspects, such as the rules and regulations governing water use and the organizational arrangements for water management, are imperative in determining whether, when, and how water reuse scheme develop and perform. It can also be a major factor which may deter or enhance the sustainability of an urban water reuse scheme. Institutions can broadly be defined as the rules, norms and practices that govern decision making and enable inclusion of the multiplicity of factors that shape water systems (Kiparsky et al. 2013). Some of these factors include public health regulations, policies, laws and other nontechnical aspects. Although a number of different reuse applications and wastewater treatment technologies are available, assessing the interaction between institutional elements and sustainability of an urban water reuse scheme may be a daunting challenge. For example, in Australia, consultation with water experts and practitioners, and review of industry and government statements, reveals a range of systemic and institutional challenges to the successful adoption of new water reclamation technologies and practices. These systematic and institutional challenges include: (i) water practitioner skills; (ii) organizational resistance (Brown et al 2009); (iii) fragmented organizational arrangements (Senate Committee 2002); (iv) regulatory regime (Environmental Business Australia 2002; United Kingdom Council of Science and Technology 2009) and (v) limited institutional capacity (Claydon 2007).

Another example provided by Roy et al. (2008) indicates that in some cases, institutional elements (e.g. capacity building, institutional designs and human resources development) have often proven to be a major hindrance to the possibilities for technological innovations aimed at encouraging sustainable water management practices such as water reuse, storm-water management. This can be aggravated by potential risk to public health and the environment and resistance to change by decision-makers and stakeholders who may prefer other alternatives to reuse. Skills requirement/capacity and insufficient standards, guidelines and regulations may apply particularly to the sustainability of water reuse initiatives. Fragmented responsibilities, lack of institutional capacity and legislative mandate all provide challenges for decision-making involving sustainability of water reuse schemes. The decision-making process may cut across different existing governing jurisdictions and institutional designs (i.e. designing institutions: the devising and realization of rules, procedures, and organizational structures that will enable and constrain behavior and action so as to accord with held values, achieve desired objectives, or execute given tasks (Alexander, E.R. (2004)); therefore it is imperative to address these challenges in order to make informed decisions that take into consideration input from different stakeholders.

As indicated by Radcliffe (2006), it is possible to successfully overcoming water industry challenges if policies are built upon innovative technology developments and innovation in regulatory management. The main research challenge is to identify and clarify the relationship between institutional arrangements/designs and water management approaches such as water reuse, and the institutional and policy conditions for continuous improvement so as to adapt to changing social and environmental circumstances. According to Blomquist et al (2004) … "there is a need to open the "black box" of institutional processes and effects, to provide explanations of how institutions matter – how they prompt people to try to change management practices, how they ease or hinder those changes, how they shape the management alternatives water users and organizations consider and adopt, and how they affect the outcomes that result".

5.5 Respondents Survey Analysis

A well-structured questionnaire was developed and administered to experts with knowledge on reuse in the SA water sector (Appendix 11). The purpose of this questionnaire, as indicated earlier, was to explore SA experts' opinions on criteria suitable for assessing the sustainability performance of urban water reuse schemes/systems for potable applications in SA over time. Detail of the questionnaire is available in appendix B. An address of a list of different experts on reuse was obtained from the Water Institute of Southern Africa (WISA) 2015 Directory (WISA, 2015). The address list contains experts' names, email addresses and membership grades. Each expert contacted was asked about their experience and knowledge on reuse. A summary of participating experts is shown in Table 5.1. A total of 115 experts were contacted, 83 responded. 51 responses were selected out of the 83 responses for further analysis on the basis of the validity of the information provided. This implies that the valid response rate is 44.3%, which is on the average acceptable for the analysis. According to Sunjka and Jacob (2013), for a research questionnaire survey, a response rate of 30% - 40% is acceptable for data analysis.

Table 5.1: Questionnaires administered to experts with knowledge on reuse in SA water sector

Respondents	**No of questionnaires administered**	**No of returned questionnaires**
Academic institutions	12	9
Water chemical manufacturer and solution provider	5	1
Government departments	8	2
Mining and Industry	5	1
Municipal officials	8	3
Water and wastewater operator	10	2
Water boards and water service provider	10	5
Water engineers and consultants	31	24
Water product supplier	6	1
Water resources management/regulatory authority	6	1
Water technology agent	7	1
Water treatment products & services	7	1
Total	***115***	***51***

5.5.1 Questionnaire Structure

The general structure of the questionnaires administered to the participant is subdivided into 3 sections.

Section 1: This section contains introduction, aim of the study and simple definitions of key words used in the questionnaire such as water reuse, criteria and types of water reuse for potable applications.

Section 2: This section requests the respondent to fill in the water sector that he/she is currently active in, requests the respondent to revise/modify the criteria (primary and secondary) supplied in the questionnaire and to suggest additional criteria and units of measurement.

Section 3: This section requests the participants to rate the importance of each criteria in the sustainability assessment process.

Section 4: Some questions asked in this section include water reuse options, appropriate effluent source for reuse, water reuse scale, sustainability indicator categories and how stakeholders can effectively participate in and contribute to strategic decision making to enhance the sustainability performance of water reuse schemes/systems in SA.

It should be noted that this questionnaire did not request for demographic information from respondents such as age, gender, marital status or racial group as it was deemed not contribute to the aim of study.

5.5.2 Data Analysis of Participating Experts' opinions

The structure of the questionnaire used in this study was described in section 5.5.2. The section of the questionnaire requesting the expert opinion on a list of items aimed at measuring the importance of the items to sustainability assessment of potable water reuse scheme over time. The items were divided into primary and secondary criteria. The primary criterion serves as the construct being measure with multiple secondary criteria/items. The experts were required to rate the degree of importance of each secondary criteria ranging from (i) not important (NI); (ii) least important (LI), (iii) important (I) and (iv) very important.

A "Likert scale" is a psychometric tool that is used to evaluate Likert items such as attitudes, values and opinions and while a Likert item is an individual statement or question which asks a person to indicate the extent to which they agree by choosing one of several ranked options (Christian Vanek, 2012). Likert-type or frequency scales use fixed choice response formats and are designed to measure attitudes or opinions (Bowling, 1997; Burns, & Grove, 1997). Examples of Likert scale is shown Table 5.2.

Table 5.2: Examples of Likert type or frequency scale (Christian Vanek, 2012)

Likert scales			
Agreement	**Frequency**	**Importance**	**Likelihood**
Strongly Agree	Very Frequently	Very Important	Almost Always True
Agree	Frequently	Important	Usually True
Neutral/Undecided	Occasionally	Moderately Important	Occasionally True
Disagree	Rarely	Of Little Importance	Usually Not True
Strongly Disagree	Never	Unimportant	Almost Never True

The term item could be anything such as questions, raters, criteria and indicators of which one might ask to what extent they "measure the same thing." Items that are manipulated are commonly referred to as variables. Some of the criteria were measured with multiple statements which made it necessary that the different statements used to assess the same primary criterion should exhibit a high internal consistencies and correlate with each other.

Cronbach's alpha coefficient is generally used to evaluate the degree to which a set of items/statements measures a single latent construct. Alpha coefficient (Cα) ranges from a value of 0 to 1, where a higher value indicates greater internal consistency and a lower value indicates lower consistency (Doloi et al. 2012; Saunders et al. 2012; Albogamy et al. 2013). Values of 0.7 and above demonstrate that the items combined in the scale are measuring the same thing (Sanders et al. 2012). However, according to Sunjka and Jacob (2013) and Nkobane (2012), Cα values of 0.5 or above are considered acceptable while in Van et al. (2015), it is said that values of Cronbach's alpha (Cα) of 0.6 and above are regarded to be acceptable. In Albogamy et al., (2013) and Doloi et al., (2012), it is stated that there is no set standard as to what an acceptable limit for the Cα value is. However, there is a rule of thumb for the interpretation of Cα values, which are: $C\alpha > 0.8$ implies excellent, $0.8 > C\alpha > 0.7$ implies good, $0.7 > C\alpha > 0.5$ implies satisfactory and $C\alpha < 0.5$ implies poor (Albogamy et al. 2013). In this study, several items (secondary criteria) can measure how well a construct (primary criterion) is performing in relation to an indicator category.

The data collected was analyzed using the Statistical Package for Social Sciences (SPSS) software. SPSS is a software package for computer data management and analysis (IBM 2011). SPSS can take data from almost any type of file and use the data to generate tabulated reports, charts, and plots of distributions and trends, descriptive statistics, and complex statistical analyses such as Cronbach's Alpha reliability analysis, factor analysis and one-way analysis of variance etc. (IBM 2011). A two-step approach was used to evaluate the expert opinions with regards to the importance of the criteria to the sustainability assessment process. The first step involved the use of the cronbach alpha value to determine if the multiple items measure the same construct. If the psychometric properties of the constructs are acceptable, the process proceeds to the second step. The second step involves the use of frequency of occurrence of "very importance" to develop the list of criteria imperative to the sustainability assessment process.

5.5.2.1 Results of the internal consistency of criteria for sustainability assessment process

The Cα values interpretation by Albogamy et al. (2013) was used in this study. Cα > 0.8 implies excellent, 0.8 > Cα > 0.7 implies good, 0.7 > Cα > 0.5 implies satisfactory and Cα < 0.5 implies poor. Table 5.3shows the Cronbach's alpha value for the measured criteria.

Table 5.3: Scale reliabilities of constructs

	Primary Criteria/Construct	Secondary Criteria/Items	Number of Items	Cronbach's Alpha	Result
ENVIROMENTAL ASPECT	Impact on surface water and reservoir quality	Nutrient removal capability of the water reuse system: Eutrophication potential - load of Nitrogen (N) present as nutrient in effluent	4	**0.382**	**Poor**
		Nutrient removal capability of the water reuse system: Eutrophication potential - load of Phosphorus(P) present as nutrient in effluent			
		Total annual fresh water saving due reuse			
		Contribution of reuse to environmental water requirement			
	Waste generation and management	Quality of sludge e.g. Heavy metal (Cd, Hg, Pb) content in sludge produced from water reuse systems/schemes	3	**0.747**	**Good**
		Quantity of sludge produced from water reuse schemes/systems			
		Waste (Sludge) recycling and reuse based on the nutrient and energy value of biosolid			

		produced from water reuse systems/schemes			
	Impact on soil quality and preservation	Spreading of toxic compound to arable land from reuse system	1	0	0
	Groundwater quality and preservation	Impact of water reuse system groundwater aquifer quality	2	**0.649**	**Satisfactory**
		BOD, suspended solids present in groundwater due to reuse			
	Contribution to climate change and air quality	Contribution of water reuse system to ambient concentration of air pollutants	2	**0.763**	**Good**
		Green-house gas emission resulting from water reuse systems/scheme calculated per unit volume			
	Natural habitat protection (wetlands and terrestrial habitats)	Impact water reuse system on habitat/wetland restoration/conservation	2	**0.759**	**Good**
		Management plan for controlling disease vectors from water reuse system			
	Land use and infrastructure compatibility	Area of available land which is used for water reuse system development	2	**0.550**	**Satisfactory**
		Ease of access to water reuse system			
	Resource utilization intensity	Total energy consumption of the water reuse system	3	**0.548**	**Satisfactory**
		Use of electricity and fossil fuels by water reuse systems			
		Quantity of chemicals used by water reuse systems e.g. Fe, Al, Cl			
ECONOMIC ASPECT	Life cycle costs	Operational cost of water reuse system	5	**0.781**	**Good**
		Maintenance costs of water reuse system			
		Payback period: length of time to recover cost of investing in water reuse system			
		Average incremental cost of adding one/more unit of production to water reuse system			
		Annualised cost: cost per year of owning and operating water reuse system			
SOCIAL ASPECT	Acceptability of reuse for potable application to stakeholders	Acceptability of reuse to user	5	**0.829**	**Excellent**
		Perceived health and safety impact due to reuse			
		Trust in water services provider			
		Willingness to use			
		Willingness to pay			
	Participation	Participation in sustainable behaviour	1	0	0
	Responsibility	Individual action to encourage water reuse scheme	1	0	0
	Public education and awareness	Public education and awareness programmes	3	**0.846**	**Excellent**
		Social inclusion			
		Community spirit			
	Impact on human health	Risk of waterborne infection as a result of reuse	4	**0.869**	**Excellent**
		Risk of gastrointestinal infection as a result of reuse			
		Cases of gastrointestinal cases reported			

		Availability of clean water			
TECHNICAL ASPECT	Design/operational capacity of water reuse systems/schemes	Water reuse systems capacity utilization	2	**0.586**	**Satisfactory**
		Skill requirement for operation and maintenance			
	Flexibility of water reuse systems/schemes	Water reuse systems flexibility to upgrade and extend	1	0	0
	Supply reliability of water reuse systems/schemes	Reliability of recycled water supply to community	2	**0.745**	**Good**
		Security of supply			
	Performance of water reuse systems/schemes	Quantity of wastewater available for reuse	5	**0.721**	**Good**
		Quality of effluent produced/supplied by water reuse scheme			
		Water quality complaints (aesthetics)e.g., odour, colour, taste			
		Water recovery rate			
		Water recovery rate			
INSTITUTIONAL ASPECT	Provisions for upgrading the skills of personnel responsible for the operation of reuse schemes	CPD points for operators/engineers for increasing skills set regarding water reuse	3	**0.756**	**Good**
		Operators training package/plans provided by water services authorities and providers to meet training needs			
		Establishment and participation in learning networks			
	Institutional cooperation between all government structures and parastatals	Appropriate coordination across all government entities on reuse	1	0	0
	National government's regulations and policies on water reuse	Tools and methods for evidence-based policy making on water reuse	3	**0.744**	**Good**
		Actions for better law implementation and enforcement			
		Tools for increased transparency and accountability			
	Support from Local government	Availability and accessibility of information and technical resources	3	**0.730**	**Good**
		Human resources strategies and policies covering the main gaps in the field of water reuse			
		Incentives and subsidy on resources utilized by water reuse scheme/system			

Items used to measure the impact on surface water and reservoir quality with Cα values of less than 0.5 were excluded while the remaining constructs were considered reliable for further analysis. Constructs measured with one item were excluded from the reliability test but were included for further analysis.

5.5.2.2 Results of the frequency of respondent's responses for different sustainability assessment process

In Table 5.4, the results of the frequency of experts' ratings ranging from 1(not important), 2(least important), 3(important) to 4(very important) are presented for the environmental aspect. The ratings reflect the importance of the secondary criteria for assessing the environmental sustainability of water reuse schemes/systems for potable applications.

Table 5.4: Frequency of experts' rating of secondary criteria assessing the environmental sustainability of an urban water reuse scheme for potable application

Primary Criteria	Secondary Criteria	Unit/(MoM)	NI	LI	I	VI	TOTAL
Waste generation and management	Quality of sludge e.g. Heavy metal (Cd, Hg, Pb) content in sludge produced from water reuse systems/schemes	mg/L	4	11	21	15	51
	Quantity of sludge produced from water reuse schemes/systems	Kg/day	5	16	18	12	51
	Waste (Sludge) recycling and reuse based on the nutrient and energy value of biosolid produced from water reuse systems/schemes	Tonnes/year	12	9	**15**	**15**	51
Impact on soil quality and preservation	Spreading of toxic compound from water reuse system to arable land	Qualitative	7	3	16	**25**	51
Groundwater quality and preservation	Impact of water reuse system on groundwater aquifer quality	Qualitative	2	4	10	**35**	51
	BOD, suspended solids present in groundwater after recharge/indirect percolation of reuse effluent into the groundwater aquifer	mg/L	10	6	19	16	51
Contribution to climate change and air quality	Contribution of water reuse system to ambient concentration of air pollutants	% of days when standards/guideline values are exceeded	9	13	20	9	51
	Green-house gas emission resulting from water reuse systems/scheme calculated per unit volume	$KgCO^2/KL$	3	16	22	10	51
Natural habitat protection (wetlands and terrestrial habitats)	Impact of water reuse system on habitat/wetland restoration/conservation	Qualitative	6	6	18	**21**	51
	Management plan for controlling disease vectors from water reuse system	Qualitative	4	5	19	**23**	51
Land use and infrastructure	Area of available land which is used for water reuse system development	Km2	9	19	16	7	51

compatibility	Ease of access to water reuse scheme	Qualitative	8	10	19	14	51
Resource utilization intensity	Total energy consumption of the water reuse systems	KWh/m^3	1	5	18	**27**	51
	Use of electricity and fossil fuels by water reuse systems/schemes	KWh/m3	2	10	22	17	51
	Quantity of chemicals used by water reuse systems e.g. Fe, Al, Cl	g/KL	3	10	25	13	51

(i) not important (NI); (ii) least important (LI), (iii) important (I) and (iv) very important (VI)

Table 5.4 presents experts' ratings of the importance of secondary criteria associated with the environmental aspect for assessing sustainability of water reuse schemes within in SA. Overall, the 51 respondents rated six secondary criteria as subsets of five primary criteria very important for assessing sustainability of the environmental sustainability of urban water reuse schemes within SA.

In Table 5.5, the results of the ratings from 1(not important), 2(least important), 3(important) to 4(very important) are presented for the economic aspect. The ratings reflect the importance of the secondary criteria for assessing the economic sustainability of water reuse schemes/systems for potable applications.

Table 5.5: Frequency of experts' rating for secondary criteria assessing the economic sustainability of an urban water reuse scheme for potable application

Primary Criteria	**Secondary Criteria**	**Unit/(MoM)**	NI	LI	I	VI	**Total**
Life cycle costs	Unit operational cost of production of water reuse system	ZAR/m3	2	1	10	**38**	51
	Unit maintenance costs of water reuse system	ZAR/m3	2	2	19	**28**	51
	Payback period: length of time to recover cost of investing in water reuse system	Years	5	8	**19**	**19**	51
	Average incremental cost of adding one/more unit of production to water reuse system	ZAR/year	5	15	20	11	51
	Annualised cost: cost per year of owning and operating water reuse system	ZAR/year	5	6	23	17	51

(i) not important (NI); (ii) least important (LI), (iii) important (I) and (iv) very important (VI)

Table 5.5 indicates experts' ratings of the importance of each secondary criterion associated with the economic aspect for assessing sustainability of water reuse schemes in SA. Overall, the respondents rated three secondary criteria very important for assessing sustainability of economical aspect of urban water reuse schemes in SA.

In Table 5.6, the results of the frequency of experts' ratings ranging from 1(not important), 2(least important), 3(important) to 4(very important) are presented for the social aspect. The ratings reflect the importance of the secondary criteria for assessing the social aspect for a sustainable water reuse schemes/systems for potable applications.

Table 5.6: Frequency of experts' ratings for secondary criteria assessing social aspect for a sustainable urban water reuse for potable applications

Primary Criteria	Secondary Criteria	Unit/(MoM)	NI	LI	I	VI	Total
Acceptability reuse for potable application to stakeholders	Acceptability of reuse to user	Percentage of survey respondents/users that find reuse for potable application acceptable	5	4	12	**30**	51
	Perceived health and safety impact due to reuse	Percentage of 'users' with concerns about injury, risk of infection	5	3	16	**27**	51
	Trust in water services provider	Percentage survey respondents who trust the WSA to provide safe reclaimed water	7	5	13	**26**	51
	Willingness to use	Percentage of 100000 population willing to use reclaimed water	7	3	15	**26**	51
	Willingness to pay	Percentage of 100000 population willing to pay for reclaimed water	8	3	16	**24**	51
Participation	Participation in sustainable behaviour	Number of people/100000 population participating in reuse initiative	6	5	22	18	51
Responsibility	Individual action to encourage water reuse scheme	Number of people willing to change behaviour/100000 population	5	3	23	20	51
Public education and awareness	Public education and awareness programmes	Percentage awareness in local community/100000 population	3	2	14	**32**	51
	Social inclusion	Percentage of 100000 population with access to information	4	5	17	**25**	51
	Community spirit	Percentage of 100000 population with access to water and sanitation infrastructure	7	9	14	**21**	51
Impact on human health	Risk of waterborne infection as a result of reuse	Number of waterborne disease outbreaks /100000 population	3	1	0	**47**	51
	Risk of gastrointestinal infection as a result of reuse	Number of affected users/ 100000 population	4	2	5	**40**	51

	Cases of gastrointestinal cases reported	Person/year	6	4	5	**36**	51
	Availability of clean water	Percentage of population with access to clean water	10	3	7	**31**	51

(i) not important (NI); (ii) least important (LI), (iii) important (I) and (iv) very important (VI)

Table 5.6indicates experts' opinions considering the importance of each criterion and unit of measurement associated with the social aspect for assessing sustainability of water reuse schemes in SA. Overall, the respondents rated twelve secondary criteria very important for assessing sustainability of technical aspect of urban water reuse scheme in a SA context.

In Table 5.7, the results of the frequency of experts' ratings ranging from 1(not important), 2(least important), 3(important) to 4(very important) are presented for the technical aspect. The ratings reflect the importance secondary criteria for assessing the technical sustainability of water reuse schemes/systems for potable applications.

Table 5.7: Frequency of experts' of ratings for primary criteria assessing the technical sustainability of an urban water reuse scheme for potable applications

Primary Criteria	Secondary Criteria	Unit/(MoM)	NI	LI	I	VI	Total
Design/operational capacity of water reuse systems/schemes	Water reuse systems capacity utilization	Ratio between design capacity and actual wastewater feed rate (%)	2	7	22	20	51
	Skill requirement for operation and maintenance	Qualitative	4	1	14	**32**	51
Flexibility of water reuse systems/schemes	Water reuse systems flexibility to upgrade and extend	Level of accommodation in design: potential and ability to accommodate future changes (qualitative)	2	5	23	21	51
Supply reliability of water reuse systems/schemes	Reliability of recycled water supply to community	Number of interruptions to supply/annum	3	2	15	**31**	51
	Security of supply	Ratio between total water delivered to customers and total demand	6	3	21	**21**	51
Performance of water reuse systems/schemes	Quantity of wastewater available for reuse	Average effluent production from water reuse scheme in KL/day	2	6	25	18	51
	Quality of effluent produced/supplied by water reuse scheme	Compliance with required standards for physical, chemical and microbial tests performed throughout the year (%)	2	2	6	**41**	51
	Water quality complaints	Number of water quality complaints/year	5	3	15	**28**	51

	(aesthetics)e.g., odour, colour, taste						
	Water recovery rate	% of water savings due to reuse	7	7	23	14	51
	Water recovery rate	% of wastewater treatment/treated due for reuse	9	9	20	13	51

(i) not important (NI); (ii) least important (LI), (iii) important (I) and (iv) very important (VI)

Table 5.7indicates experts' ratings of the importance of each secondary criterion with the technical aspect for assessing sustainability of water reuse schemes in a SA. Overall, the respondents rated five secondary criteria very important for assessing sustainability of technical aspect of urban water reuse scheme in SA.

Table 5.8, the results of the frequency of experts' ratings ranging from 1(not important), 2(least important), 3(important) to 4(very important) are presented for the institutional aspect. The ratings reflect the importance of the secondary criteria for assessing the institutional sustainability of water reuse schemes/systems for potable applications.

Table 5.8: Frequency of experts' ratings for primary criteria assessing institutional sustainability of urban water reuse scheme for potable applications

Primary Criteria	Secondary Criteria	Unit/(MoM)	NI	LI	I	VI	Total
Provisions for upgrading the skills of personnel responsible for the operation of reuse schemes	CPD points for operators/engineers for increasing skills set regarding water reuse	Hours/annum	7	13	17	14	51
	Operators training package/plans provided by water services authorities and providers to meet training needs	Qualitative	3	3	14	**31**	51
	Establishment and participation in learning networks	Qualitative	6	9	20	16	51
Institutional cooperation between all government structures and parastatals	Appropriate coordination across all government entities on reuse	Qualitative	3	8	14	**26**	51
National government's regulations and policies on water reuse	Tools and methods for evidence-based policy making on water reuse	Qualitative	3	3	24	21	51
	Actions for better law implementation and enforcement	Qualitative	2	4	19	**26**	51
	Tools for increased transparency and accountability	Blue drop score	3	5	13	**30**	51
Support from Local government	Availability and accessibility of information and technical resources	Qualitative	8	5	16	**22**	51
	Human resources strategies and policies covering the main gaps in the field of	Qualitative	3	6	18	**24**	51

	water reuse						
	Incentives and subsidy on resources utilized by water reuse scheme	% of subsidy received from government on resources utilized	4	6	19	**22**	51

(i) not important (NI); (ii) least important (LI), (iii) important (I) and (iv) very important (VI)

Table 5.8presents experts' rating of the importance of secondary criteria associated with the institutional aspect for assessing sustainability of water reuse schemes in SA. Overall, the respondents rated seven secondary criteria very important for assessing sustainability of institutional aspect of urban water reuse scheme in SA.

5.6 Conclusion

The experts' opinions on the set of secondary criteria which by rating from not important to very important, is a reflection of their importance and relevancy to the SA context, suggests the exclusion of some criteria (primary and secondary). Several recommendations were thus made with respect to reducing the overall number of criteria (primary and secondary) as well as being more strategic about those to be included and excluded as shown in Table 5.9. This study put into perspective their relevance and importance to the SA context. Furthermore, this study provided detailed information on what is to be measured with respect to urban water reuse sustainability reporting in SA. The preliminary group of criteria comprises of 22 primary criteria and 53 secondary criteria and the final group of criteria comprises of 16 primary criteria and 27 secondary criteria as shown in Table 5.9.

Table 5.9: Primary and secondary criteria associated with each sustainability aspect.

Aspect	Preliminary number of criteria (primary and secondary)		Number of criteria (primary and secondary)	
	Primary	**Secondary**	**Primary**	**Secondary**
Environmental	8	14	5	6
Economic	2	5	1	2
Technical	4	10	3	4
Social	5	14	3	8
Institutional	4	10	4	7
Total	**22**	**53**	**16**	**27**

Although the participants commented that the criteria are all important, however for this study and in order to reduce the number of items, the "very important" secondary criteria were taken into consideration to be included in the final list. In some cases, there were contentions regarding location of some secondary criteria amongst some respondents e.g., risk of gastrointestinal infection as a result of reuse should fall under risk of waterborne infection as a result of reuse. This aim of this study was to determine a set of criteria for sustainability assessment of urban water reuse scheme. Furthermore, it is likely that the vision of a sustainable water reuse initiative will be redefined prompting the addition of different criteria and/or the modification of the ones highlighted in this study. Table 5.10 shows the list of sustainability assessment criteria as indicated by the experts consulted.

Table 5.10: Final list of criteria (primary and secondary) rated "very important"

Aspect	Primary Criteria	Secondary Criteria	Unit/(MoM)
Environmental	Waste generation and management	Waste (Sludge) recycling and reuse based on the nutrient and energy value of biosolid produced from water reuse systems/schemes	% of sludge produced that can be reused for other beneficial purposes
	Soil quality and preservation	Spreading of toxic compound from reuse system to arable land	Qualitative
	Groundwater quality and preservation	Impact of water reuse system on groundwater quality and preservation	Qualitative
	Natural habitat protection (wetlands and terrestrial habitats)	Impact of water reuse system on habitat/wetland restoration/conservation	Qualitative
		Management plan for controlling disease vectors from water reuse system	Qualitative
	Resource utilization intensity	Total energy consumption of the water reuse systems	KWh/m^3
Economic	Life cycle costs	Unit operational cost of production of water reuse system	ZAR/m3
		Unit maintenance costs of water reuse system	ZAR/m3
Technical	Design/operational capacity of water reuse systems/schemes	Skill requirement for operation and maintenance	Qualitative
	Reliability of water reuse systems/schemes	Security of water supply to community	Number of interruptions to supply/annum
	Performance of water reuse	Quality of effluent produced/supplied by water reuse scheme	Compliance with required standards for physical,

	systems/schemes		chemical and microbial tests performed throughout the year (%)
		Water quality complaints (aesthetics)e.g., odour, colour, taste	% Number of reclaimed water quality complaints/year
social	Acceptability to stakeholders	Acceptability of reuse to stakeholder	Percentage of survey respondents/users that find potable reuse acceptable
		Perceived health and safety impact due to reuse	Percentage of survey respondents/users with concerns about injury, risk of infection
		Trust in water services provider	Percentage survey respondents who trust the WSA to provide safe reclaimed water
	Public education and awareness	Public education and awareness programmes	Percentage of survey respondents' awareness on reuse
		Social inclusion	Percentage of survey respondents living in formal dwellings
		Community spirit	Percentage of survey respondents willing to engage in activities to encourage reuse
	Impact on human health	Risk of waterborne infection as a result of reuse	Percentage of survey respondent awareness of incident of disease outbreak
		Availability of clean water	Percentage of survey respondents with piped water inside dwelling
Institutional	Provisions for upgrading the skills of personnel responsible for the operation of reuse schemes	Operators training package/plans provided by water services authorities and providers to meet training needs	Qualitative
	Institutional cooperation between all government structures and parastatals	Appropriate coordination across all government entities on reuse	Qualitative
	National government's regulations and policies on water reuse	Actions for better law implementation and enforcement	Qualitative
		Tools and methods for evidence-based policy making on water reuse	Quantitative
	Support from Local government	Information and technical resources	Qualitative
		Human resources strategies and policies covering the main gaps in the field of water reuse	Qualitative

		Incentives and subsidy on resources utilized by water reuse scheme	Qualitative

These criteria (primary and secondary) developed from this study will be used to measure sustainability performance of water reuse schemes in SA communities. Therefore, questions such as what a sustainable water reuse scheme is and how the sustainability of the scheme can be assessed can be answered as this is imperative to the overall success of water reuse schemes and the movement towards contributing to a low carbon, sustainable society. These criteria can be used as a baseline tool by water and wastewater plant operators, water boards and water services providers to evaluate the sustainability of the existing schemes. It can also serve as a guideline for designing and developing water reuse schemes in SA communities where water reuse schemes are to be implemented.

5.7 Summary

As highlighted in previous sections, there are some vital challenges to sustainability of water reuse for potable application. Assessing sustainability of water reuse schemes involves a multidisciplinary approach that incorporates technical, economic, environmental, institutional and social factors. The starting point is to identify the challenges face water reuse sustainability, identification and development and selection of criteria that cut across five attributes of sustainability for the assessment process. Criteria developed, selected and grouped under specific sustainability attributes can simultaneously evaluated to adequately describe sustainability assessment process. The key criteria cover issues such (i) water quality and security of supply; (ii) water treatment technology; (iii) Cost relative to other water supply alternatives; (iv) Social and cultural perceptions and (v) Environmental considerations; that affect choices related to water reuse as an option for water supply and augmentation. In order to enhance the robustness and practicality of the ISI, experts in SA water sector with knowledge on reuse were consulted for development and selection of sustainability assessment process. It is imperative that the assessment criteria provide a broad picture of the factors that suit a South African reuse schemes in a holistic approach for the sustainability assessment process.

CHAPTER 6

6 TECHNICAL, ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF WATER REUSE SUSTAINABILITY

6.1 Introduction

The SA Department of Water affairs and Sanitation has set some objectives against which water management strategies of water institutions and service providers or consumers (to influence water demand and supply) should be measured (Adewumi, 2011). According to Ilemobade et al., (2009), these objectives include:

(i) environmental protection,

(ii) social development,

(iii) economic efficiency

(iv) social equity

(v) sustainability of water supply and services

(vi) political acceptability

These objectives form the foundation upon which the framework of the developed integrated sustainability index (ISI) of this research work is built. This chapter presents the framework adopted in the development of the ISI. According to Adewumi, (2011), traditional decision making tools tend to focus quantifiable factors while equally important non-quantifiable factors that may have significant impact on a project are left out. The evaluation of quantifiable and non-quantifiable factors will assist in covering a broader base on issues of relevant importance that may considerably impact a water reuse project. Water reuse is an established approach as part of alternative water management strategies. Some key considerations that affect reuse as an alternative for water supply and augmentation that require comprehensive investigation include (i) Water quality and security of supply; (ii) treatment technology; (iii) social and cultural perceptions; (iv) environmental consideration and (v) cost relative to other water supply options (National Strategy on Water Reuse (NSWR), 2011). The thorough investigation of these key issues affecting reuse projects will be difficult to perform without an assessment tool that will provide a synopsis of the task to be performed. Consultation with water experts and practitioners with knowledge on reuse in SA water sector reveals a range of technical, environmental and economic criteria for investigating these key issues. These criteria form the pivot upon which the ISI of the work was developed.

Table 6.1: Links between the DWA (NSWR) criteria and the ISI

DWA (National Strategy for Water Re-use) Key Criteria/Considerations	**Integrated Sustainability Index (ISI)**
Assessment of treatment technology employed by specific water reuse scheme for potable application	**Technical Assessment** • Design/operational capacity of water reuse systems/schemes • Reliability of water reuse systems/schemes • Performance of water reuse systems/schemes
Economic efficiency of alternative water management strategy (i.e. reuse system for specific potable application)	**Whole life-cycle cost** • Unit Operational cost • Unit maintenance cost
Environmental considerations and protection (Soil, surface and ground water aquifers)	• Waste generation and management • Soil quality and preservation • Groundwater quality and preservation • Natural habitat protection (wetlands and terrestrial habitats) • Resource utilization intensity
Social perceptions to determine acceptability, institutional capabilities and characteristics, public education and awareness on reuse for potable applications	**Perception Survey** Reclaimed water users perception • Download and print questionnaire • Analyze questionnaire • View the analysis results **Institutional capabilities and characteristics** • Skills and capacity building • Institutional arrangement • Policies and regulations • Support from tiers of government

The next section provides a framework for the assessment of the technical, environmental and economic criteria used in the ISI. A schematic flow chart of the framework is shown in Figure 6.1.

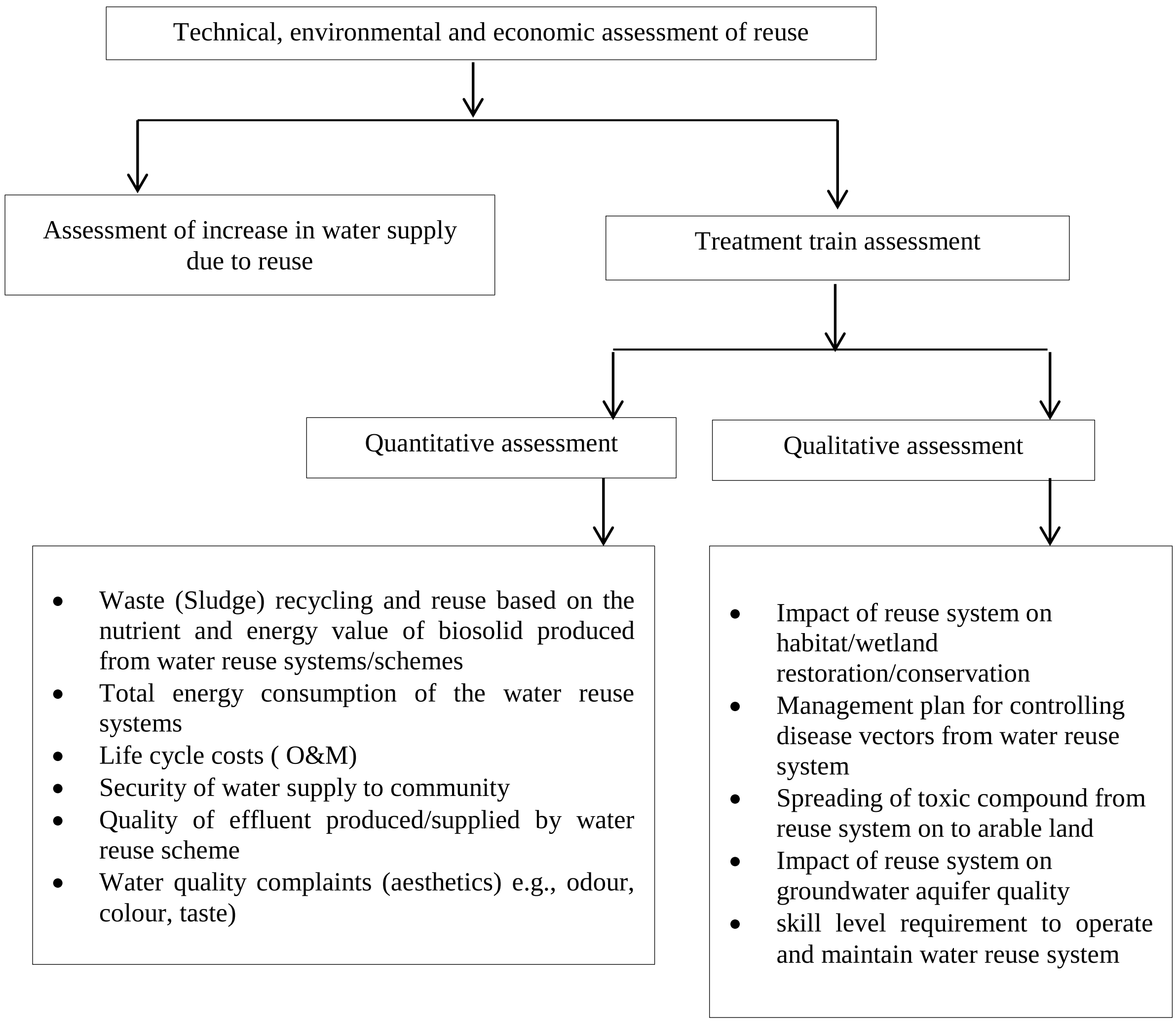


Figure 6.1: Schematic flow chart of the technical, environmental and economic assessment

The framework provides a robust structure for assessing water reuse sustainability for potable applications and is designed to provide decision makers with both quantitative and qualitative criteria that cut across technical, economic and environmental attributes of sustainability while the social and institutional attributes are discussed in Chapter 6.
In this way, a more balanced view is created rather than one that relies on only quantifiable factors (Ilemobade et al., 2009).

6.2 Assessing Water Savings Due to Reuse

The amount of wastewater generated, treated and used for direct or indirect potable application will determine the water savings due to reuse. In most cases, reclaimed wastewater is primarily used for non-potable applications. However, in practice with appropriate treatment, reclaimed water usage has been extended to direct reuse for potable applications in countries such as Singapore, Beaufort West-SA, and Windhoek-Namibia. Utilization of reclaimed water for potable uses varies from location to location depending on the adopted alternative water management strategy and freshwater availability. To quantitatively estimate the share of potable water demand that can be covered by reclaimed water can be an arduous task where volumetric information is not readily available -as this is the case in most developing countries. This problem is further amplified by the reasons highlighted by Grobicki and Cohen (1999) in their study on water reclamation for direct potable reuse in SA. These reasons include:

1. Information and responses from public institutions at local and national levels are difficult to come by due to the size of the relevant institutions which makes it difficult to identify individuals responsible for specific tasks. Apparently, individuals within each institution are not aware of what others within the same institutions are doing as well.
2. Secondly, precisely in institutions undergoing internal changes, information is being lost in transit or not readily available/accessible due to physical office relocations which is also tantamount to ill-defined roles and duties of an individual with the institutions.
3. In a situation where information does exist, the data is often found to be incomplete and tedious to collate. In some instances, information only exists in a handwritten format for record keeping which makes it difficult to access and analyze.
4. The contradiction of numerical data obtained from different sources for the same area.

The study by Carden (2013) also corroborated data availability constraint in SA regarding water resources management project. In the absence of volumetric information, water savings due to reuse for potable applications can be assessed using a mathematical representation of the portion of potable water demand that can be covered by reclaimed water. This volumetric information can be evaluated using various mathematical equations described in the next sections. This section of this study is aimed at elucidating the systematic framework employed in estimating water saving due to reuse as part of the module in the decision support tool (DSS) developed in this study. This module is envisioned to assist water resources managers in estimating water savings due to reuse where no volumetric information exist or not readily available.

Several studies have sought to estimate wastewater reuse potential without details explanation of the methods used to determine the estimate. Moreover, previous studies (such as Angelakis and Diamadopolous, 1995; Alexopoulous, 1996; Barbagallo et al. 2000; and Angelakis et al. 2003) do not take into consideration the share of water demand that can be saved due to reuse. For an European context, Hoschstrat et al. (2005) presented a model for estimating water reuse potential on the assumption that reclaimed water reused is equal to the amount of treated effluent from water reclamation plant. However, the model was limited in providing a method of estimating wastewater return flow generated from urban water consuming activities. This study puts forward a modified mass balance approach for evaluating water savings due to reuse. It is imperative to estimate the volume of wastewater that can be generated which invariably can be treated and available for reuse.

6.2.1 Estimation of the Constituents of Wastewater Return Flow

In this study, it is assumed that the current practice for water supply and wastewater conveyance occurs on a centralized supply, conveyance and treatment basis as shown in Figure 6.2 where water treatment plant (WTP), wastewater treatment and water reclamation plant (WRP).

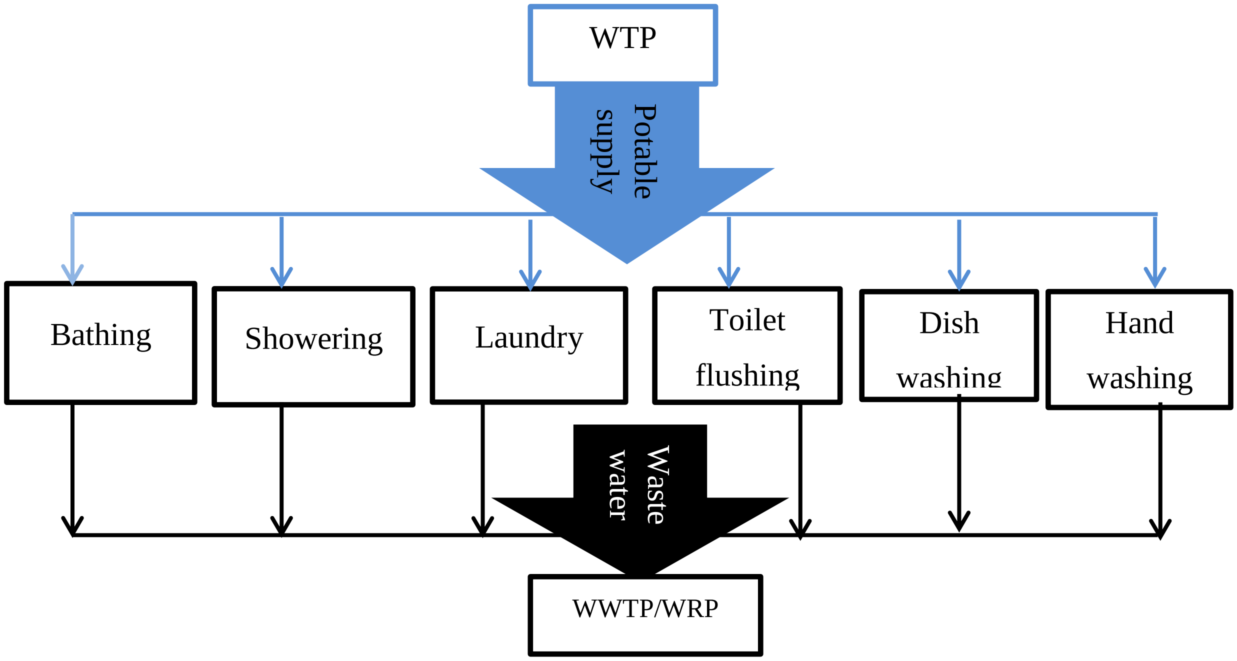


Figure 6.2: Water supply, wastewater generation and conveyance

In order to estimate the wastewater generated in an urban residential area, we considered wastewater generated from 6 domestic activities: bathing, flushing, hand washing, dish washing, showering and laundry. Based on the researches by Jacob (2004), the Rand Water Corporation Report and Van Zyl et al. (2007), Table 6.2illustrates the values assigned to the relevant volumes and frequencies of these activities with regards to the specific income areas. A set of equations were adopted to estimate the wastewater return flow from six domestic activities from a residential unit. The approximation equation used for the development of the volumetric flow of wastewater in this study was a modified version of the equation presented by Memon et al. (2005) (equation 6.1).

Table 6.2: Examples of frequency and volumes of water consumption for domestic activities for different incomes classes in SA. (Jacob (2004), Van Zyl et al. (2007))

Parameter	High income	Middle income	Low income/Township	Informal settlement/ RDP	Units
Bath frequency	0.5* 0.6**	0.78* 0.5**	0.5**	0.65* 0.7**	Use/person/day
Bath volume	100**	80**	50**	20**	l/use
Shower volume	80**	60**	50**	40**	l/use
Shower frequency	0.6**	0.6**	0.5**	0.3**	Use/person/day
Toilet flush volume	15**	15**	12**	12**	l
Toilet flush frequency	4**	3**	2.5**	2.5**	flushes/ person/day
Laundry machine volume	30**	30**	0	0	l/wash
Laundry frequency	0.5**	0.4**	0	0	washes /person/day
Dishwasher volume	30**	30**	0	0	l/wash
Dishwasher frequency	0.5**	0.4**	0	0	washes /person/day
Onsite leakage return to sewer	6**	8**	10**	10**	l/stand/day
On-site leakage not returned	3**	4**	5**	5**	l/stand/day

***Study by Jacob (2004), **Study by Van Zyi et al. (2007)**

Equation 6.1is based on the concept of return flow contributing to grey water generation from bathing, showering and hand washing expressed in terms of the frequency of activity and the volume of water consumed by the activity.

$$T_{bv} = b_v \, D \, F_b N_r \quad \dots\dots\dots\dots\dots\dots.. equation\ 6.1$$

Where,

T_{bv} = the total bath volume (l/day)

b_v = bath volume (l/use)

F_b = is frequency of baths (uses/person/day)

D = average number of days per year grey-water is produced

N_r = number of residents.

However in this study, the contribution to wastewater return flow from the six activities is expressed in terms of the frequency of activity, volume of water use, losses due to onsite leakage and percentages of houses connected to the sewer system. The wastewater return flow equations used in this study are highlighted below:

a. ***Return flow from bathing activity***

$$TV_b = \frac{365}{1000}(V_b\, FR_b\, P_n\, HC_s) \quad \dots\dots\dots\dots\dots\dots\dots . equation\ 6.2$$

Where,

TV_b = total bath volume (m^3)

V_b = volume of bath (l/use)

FR_b = frequency of baths (use/person/day)

P_n = number of people/residents

HC_s = Percentage of house connected to sewer

b. ***Return flow from showering activity***

$$TV_s = \frac{365}{1000}(V_s\, FR_s\, P_n\, HC_s) \quad \dots\dots\dots\dots\dots . equation\ 6.3$$

Where,

TV_s = total shower volume (m^3)

V_s = shower volume (l/use)

FR_s = frequency of showers (uses/person/day)

P_n = the number of people/residents

HC_s = Percentage of house connected to sewer

c. ***Return flow from hand washbasin activity***

$$TV_h = \frac{365}{1000}(V_h\, FR_h\, P_n\, HC_s) \quad \dots\dots\dots\dots .. equation\ 6.4$$

Where,

TV_h = total hand washbasin volume (m^3)

V_h = hand basin volume (l/use)

FR_h = frequency of hand washbasin uses (uses/person/day)

P_n = number of people/residents

HC_s = Percentage of house connected to sewer

d. Return flow from toilet flushing activity

$$TV_f = \frac{365}{1000}\left(V_f\, F_f\, P_n\, HC_s\right) \ldots\ldots\ldots\ldots.. equation\ 6.5$$

Where,

TV_f = total toilet flushing volume (m^3)

V_f = volume of toilet cistern (l/use)

F_f = toilet flush frequency (uses/person/day)

P_n = number of people/residents

HC_s = Percentage of house connected to sewer

e. Return flow from laundry activity

$$TV_l = \frac{365}{1000}\left(V_l\, F_l\, P_n\, HC_s\right) \ldots\ldots\ldots\ldots.. equation\ 6.6$$

Where,

TV_l = total laundry volume (m^3)

V_l = water consumption (litres) per standard cycle by the machines' capacity (kilograms for a full load)

F_l = frequency of laundry

P_n = number of people/residents

HC_s = Percentage of house connected to sewer

f. Return flow from dish washing activity

$$TV_d = \frac{365}{1000}\left(V_d\, F_d\, P_n\, HC_s\right) \ldots\ldots\ldots\ldots.. equation\ 6.7$$

Where,

TV_v = total dish washing volume (m^3)

V_d = water consumption (litres) per standard cycle by the machines' capacity (kilograms for a full load)

F_d = frequency of dish washing activities

P_n = number of people/residents

HC_s = Percentage of house connected to sewer

g. On-site leakage to sewer

Generally, on-site leakage is directed to the sewer, hence, equation 6.8 is used to estimate the volume of wastewater returned to sewer due to leakages from toilets or indoor taps.

$$OS_r = \frac{365}{1000}\,(LR_s \times HS_n)\,HC_s \quad \ldots\ldots\ldots\ldots equation\ 6.8$$

Where,

OS_r = total on-site leakage returned to sewer

LR_s = On-site leakage (l/stand/day)

HS_n = number of stands/houses

HC_s = Percentage of houses connected to sewer

6.2.2 Estimation of Usable Wastewater Return Flow

Therefore, the total wastewater generated as return flow from the highlighted domestic activities was estimated using equation 6.9 below:

$$TV_w = TV_b + TV_s + TV_h + TV_f + TV_l + TV_d + OS_r \quad \ldots\ldots\ldots\ldots equation\ 6.9$$

Where:

TV_w = total volume of wastewater generated (m^3)

In order to estimate the volume of feed-water to water reclamation plant, equation 6.10 below was formulated.

$$CN_I = TV_w \times LF_c \quad \ldots\ldots\ldots\ldots equation\ 6.10$$

$$WR_{fw} = TV_w - CN_l \quad \ldots\ldots\ldots\ldots equation\ 6.11$$

Where,

WR_{fw} = volume of feed-water to water reclamation plant

TV_w = total volume of wastewater generated (m^3)

CN_l = leakage due to sewer conveyance (m^3)

LF_c = conveyance leakage factor ($0\% \le LF_C \le 30\%$)

6.2.3 Estimation of Water Saved due to Reuse Factor θ

The volumetric flow of reclaimed water is estimated using equation 6.11. In this study, we introduce filtrate recovery rate factor. The filtrate recovery rate factor of the selected treatment trains technologies is based on the efficiency of the system to produce maximum volume of filtrate from the feed-water. Furthermore, in this study, the domestic water demand was estimated using equation 6.12. Therefore, the fraction of total water demand covered by reclaimed is described as the potable water saving factor which is estimated using the equation 6.13 below:

$$VF_r = WR_{fw} \times FL_r \ldots\ldots\ldots\ldots equation\ 6.11$$

$$WD_t = \frac{365}{1000}\,(WU_s \times P_n) \quad \ldots\ldots\ldots\ldots equation\ 12$$

$$\theta = \frac{2VF_r - \left(WR_{fw} \times FL_r\right)}{WD_t} \times 100\% \quad \ldots\ldots\ldots\ldots equation\ 6.13$$

Where,

$\theta =$ potable water saving factor

$WU_s =$ daily water consumption (l/person/day)

$WD_t =$ domestic water demand/consumption (m^3)

$WR_{fw} =$ volume of feed-water to water reclamation plant (m^3)

$FL_r =$ Filtrate recovery rate factor (%) $(0\% \leq FL_r \leq 100\%)$

$VF_r =$ Volumetric flow of reclaimed water (m^3)

6.3 Treatment Technology Train Assessment of Reuse for Potable Applications

Over the years, technological advancements have opened doors to varieties of treatment train technology to ensure that reclaimed water meets "fit for purpose" end use or applications. Some significant challenges faced by decision makers include technical issues such as appropriate optimum treatment process configurations, treatment process reliability and real time monitoring requirements. As more water service providers and communities are beginning to explore the feasibility of water reuse for potable applications as well as the long term sustainability of existing ones, decision influencing parameter such appropriate optimum treatment process configurations must be addressed.

6.3.1 Information on Treatment Technology Train Processes for Reuse for Potable Applications

The first step in treatment train assessment process is to highlight the principal technologies units use for advanced treatment for production of reclaimed water for potable applications. The treatment technologies consist of treatment unit processes from primary, secondary and advanced treatment processes including both conventional and innovative options as shown in Table 6.3.

The preliminary treatment unit is essential for the removal of coarse solids and any large suspended solids in unfiltered and filtered treated wastewater. No major pollutants present in the wastewater stream are removed at this stage. However, they are essential for protection of downstream membranes thereby increasing the efficiencies of the downstream treatment processes. Five unit processes were incorporated into the knowledge base of the DSS under preliminary treatment. Secondary treatment units utilize a combination of chemical and physical processes to treat partially treat effluent from the preliminary treatment units. These secondary treatment units are saddled with the responsibility of removal of all macro-organic matters and the remaining suspended solids. Six unit processes were considered in this category.

In most direct potable water reclamation plants, the equalization basin unit is an integral part of the secondary treatment unit. It is used regulate variations in flow rate and water quality. It is imperative that that the advanced treatment units is supplied with tertiary effluent with consistent flow rate and water quality in order reduce tear and wear on process units for improved performance. The advanced treatment units consist of series of membrane filtration technologies of different pore sizes utilized for the removal of micro-pollutants.

Table 6.3: Summary of water reclamation technologies included in the ISI

Treatment Stage	Unit Process
Preliminary treatment	Filter screens
	Dissolved air floatation
	Coagulation/flocculation
	Sedimentation (w coagulant)
	Sedimentation (w/o coagulant)
Secondary treatment	Flow equalization basin
	Neutralization reactors
	Membrane bioreactor
	Precipitation reactor
	Rapid sand filtration
	Hydrocyclones
Advanced Treatment	Nano filtration
	Micro filtration
	Ultra filtration
	Granular media filtration
	Cartridge filtration
	Reverse osmosis
	Electrodialysis
	Advanced oxidation
	Granular activated carbon
	Biological activated carbon
	Ion exchange
Disinfection	Chlorine contactor
	UV radiation
	Ozonation
	Chlorine dioxide

Micro-filtration (MF) and ultrafiltration (UF) units are utilized for the removal of residual suspended particles by mechanical sieving. Typically, UF is often used instead of MF. The electrodialysis and ion exchange processes are used for the removal of salts, reduction of hardness or removal of nitrogen, heavy metals and total dissolved solids from solution by the use of selective membrane. Nano-filtration is used for the removal of residual suspended and polyvalent cations from secondary treated effluent by mechanized sieving process. RO unit is used for the removal of residual salts, organic traces, colloidal and dissolved solids by means of diffusion and size exclusion. Granular/biologically activated carbons are used to remove negative ions (e.g. ozone, chlorine, fluorides and dissolved organic solutes) from water by absorption. Advanced oxidation process is used to oxidize complex organic constituents into simpler end product by destroying or altering the chemical composition of compounds that are not oxidized completely by conventional biological treatment processes or removed by the filtration units.

Disinfection units are the final stage included in the treatment processes. Ozone with hydrogen peroxide or Ultraviolent disinfection with hydrogen peroxide are disinfecting agents that have been used overtime to address the microbial constituent of concerns in treated effluent. The use of chlorine dioxide and chlorine gas through the chlorine contactor unit also serves the purpose of disinfection.

6.3.2 Synthesis of Treatment Technology Trains

Rossman (1989) first introduced the concept of synthesis a wastewater treatment train in the development of the EXEC/OP model that was aimed at generating a set of design alternatives for municipal wastewater treatment (Joksimovic, 2006). Adewumi, (2011) defined this synthesis as the specification of a system (the choice and arrangement of unit processes and operations) and the design of individual units within that system so that design objectives are fulfilled. Rossman (1989) also developed a hybrid methodology to generate a number of alternatives which included a structured knowledge base containing the following information (Joksimovic, 2006):

a) List of treatment technology unit processes and information for estimating their individual performance;
b) Rules for excluding a treatment technology unit process based on acceptable configurations and spatial limitations;
c) Treatment technology unit process pre-treatment requirements; and
d) Measures for evaluating the real and pseudo-costs.

Different methods have been explored by several researchers to generate wastewater treatment technology units. Liaw and Chang, (1987) and Gasso et al., (1992) used the bounded implicit enumeration approach in the preliminary design of wastewater treatment systems to synthesize the least cost design. This methodology entails a systematic selection of different treatment technology unit processes to form treatment trains with the least cost estimate. Several studies have developed expert systems for solving challenges facing urban water management. In particular, the introduction of alternative water management strategies such as selection of optimal treatment unit processes, disposal and assessing the feasibility of implementing water reuse projects (Wee and Krovvidy, 1990; Krovvidy, et al., 1994; Chen and Beck, 1997; Ahmed et al., 2002; Economopoulou and Economopoulos, 2003; Dinesh and Dandy, 2003; Joksimovic et al., 2006; Joksimovic, et al., 2008, Adewumi, 2011). An expert system is a computer program that emulates the decision making ability of a human being or simulates the judgment and behavior of a human being that has expert knowledge and experience in a particular field. Expert systems can be divided into two subsystems namely: (i) the knowledge base and (ii) the inference engine (thinking machine). The knowledge base subsystem contains accumulated experiences which represent facts and rules while the inference engine applies the rules to the known facts to deduce new facts to solve the problem representing a particular situation that is described to the program.

Bick and Oron (2004) and Addou et al. (2004) employed the analytical hierarchy process (AHP) for selection of wastewater treatment technologies. AHP provides a rational basis to structure complex decision making problems into overall objectives and evaluating individual alternative solutions thereby recommending a preferred solution. This approach breaks down the complex problem into a hierarchy of sub problems that can then be analyzed individually and independent of the other sub-problems as well. Once the sub-problems are arranged into hierarchy, the decision makers systematically evaluate its various representative assessment criteria with the relative importance of these criteria which is determined through a pairwise comparison exercise. The AHP converts these assessments criteria into a set of weights which are numerical values incorporating judgments and personal values of the decision makers for comparison over the entire range of the problem. A numerical weight is derived for each criterion of the hierarchy using a simple additive weighting method, allowing diverse and often tangible and intangible criteria to be compared to one another in a rational and consistent way to derive the ranking of the preferred solution/alternative. Barzilai and Golany (1994) criticized the soundness of AHP in decision making due to issues of normalization and rank reversal despite its popularity.

Multi-criteria analysis (MCA) is a structured methodology for supporting decision-making when dealing with more than a single criterion and allows relative importance to be placed upon each criterion by the user (Resource Assessment Commission 1992). Hidalgo et al. (2007) employed the MCA methodology to develop a decision support system to promote safe water reuse in an urban context. Some of the decision influencing criteria considered by the study for the development of the DSS includes treatment unit technology, land requirements, cost, soil types, weather-related conditions, legislative requirements, types of crops cultivated and their water requirements. The analysis assigned weights to these various criteria to score the safe reuse of wastewater effluent.

Ellis and Tang (1990) and Tang and Ellis (1994) also employed the MCA approach with focus on 20 parameters that permeate across environmental, technical, economic and socio-cultural factors to form a decision matrix for ranking 46 wastewater treatment processes. Of interest to this research work are the models developed using expert systems. Most of these models are rule- based models that use fuzzy logic based approaches to capture the user's preference for selection of treatment unit processes. The selection of the treatment unit processes is defined on the basis of the treatment unit efficiency and the cost of a treatment unit process. Rules are represented with the if-then constructs.

Table 6.4 Decision support systems for wastewater reuse using expert system (Adapted from Adewuni, 2011)

Name of Decision Support System	Acronym	References
Sequence Optimizer for Wastewater Treatment	Sowat	Krovvidy, et al., 1994
Water and Wastewater Treatment Technologies Appropriate for Reuse	WAWTTAR	Finney and Gearheart, 1998
Model for Optimum Selection of Technologies for Wastewater Treatment and Reuse	MOSTWATER	Dinesh and Dandy, 2003
Water Treatment for Reuse with Network Distribution	WTRNet	Joksimovic et al., 2006 AQUAREC, 2006 Joksimovic, 2006 Joksimovic, et al., 2008
Waste water reuse planning model	WASWARPLAMO	Adewuni, 2011

For example, IF compound = X and influent concentration is between A and B AND technology = Y THEN effluent concentration is between C and D (Joksimovic, 2006).

MOSTWATER, WTRNet and WAWTTAR DSSs considered both quantitative and qualitative assessments of factors that permeate across environmental, economic and technical, economic attributes associated with individual treatment unit processes while economic factors and technical functionality were the basis for the SOWAT DSS.

Limitations of factors considered by Ellis and Tang (1990) and Tang and Ellis (1994) in their studies include the non-flexibility of the factors and the factors have proven to be too ambiguous to use in other locations. However, some important factors like social perceptions, institutional capacities and characteristics which are pivotal to implementation and sustainability of reuse projects were not included in these models. Furthermore, these models are limited in incorporating these interdisciplinary and multidisciplinary factors affecting reuse into an indicator or barometer. Thereby, promoting a holistic understanding of water reuse sustainability and providing a platform for systematic integrated analysis of these influencing factors associated with water reuse. The ISI developed in this research work uses multi-criteria factors in assessing water reuse sustainability for potable applications in SA communities. The technical assessment methodology for this research will be adapted from WASWARPLAMO (Adewumi et al. 2012), and WTRNet (Joksimovic, 2006).

6.3.2.1 Methodology for Generating of Advanced Treatment Trains for Potable Reuse

It is interesting to know that a number of different unit processes can be combined for removal of pollutants from wastewater to achieve a fit for purpose reclaimed/recycled water. The combination of these unit processes can be a tedious exercise which implies that the treatment unit processes employed has to be from among the varieties of treatment unit processes to form standard treatment trains for potable reuse purposes. The methodology for generating treatment flow and technology will be based on selection from among various treatment flow processes and technology for standard potable reuse purposes. The following rules will be used for developing a knowledge base for assembling treatment flow and technology (Joksimovic, 2006; Kubik and Hlavinek, 2005, as cited in Adewumi et al. 2012):

a. rules that dictate possible starting points (unit processes) depending on the influent water quality,
b. rules that prohibit the formation of unacceptable process configurations that violate sound engineering practice, and
c. rules to check if the required pre-treatment or the maximum allowable quality requirement for unit processes are met.

The following expression will be the general rules structure: ***IF (unit process A / unit process (es) from category X) IS (present / absent) THEN (unit process (es) B / unit process (es) from category Y) (can / must / cannot) be present*** (Adewumi et al. 2012).

6.4 Treatment Train Assessment Criteria

Treatment train assessment criteria used in this research work are criteria developed from previous study in chapter four on consultation with water experts and practitioners with knowledge on reuse in SA water sector which reveals a range of economic, environmental and technical criteria for successful adoption and sustainability of water recycling technologies and practices. The technical criteria considered are design/operational capacity, performance and reliability of water reuse systems. The environmental criteria considered are resource utilization intensity, waste generation and management, groundwater quality and preservation and natural habitat protection (wetlands and terrestrial habitats) while economic criteria relates to the project life cycle costs (i.e. operating and maintenance etc.). Table 6.5 present a summary of the above.

Table 6.5: Classification of technical, environmental and economic assessment criteria

Criteria	Primary Criteria	Secondary Criteria
Quantitative Technical	Design/operational capacity of water reuse systems/schemes	Operation and maintenance skill requirement
Qualitative Technical	Reliability of water reuse systems/schemes	Security of water supply to community
	Performance of water reuse systems/schemes	Quality of effluent produced/supplied by water reuse scheme
		Water quality complaints (aesthetics)e.g., odour, colour, taste
Quantitative Environmental	Resource utilization intensity	Total energy consumption of the water reuse systems
Quantitative Economic	Life cycle costs	Unit operational cost
		Unit maintenance cost
Quantitative Environmental	Waste generation and management	Waste (Sludge) recycling and reuse based on the nutrient and energy value of biosolid produced from water reuse systems/schemes
Qualitative Environmental	Impact on arable land	Impact of water reuse system on soil quality
	Groundwater quality and preservation	Impact of water reuse system on groundwater aquifer quality
	Natural habitat protection (wetlands and terrestrial habitats)	Impact of water reuse system on habitat/wetland restoration/conservation
		Management plan for controlling disease vectors from water reuse system

6.4.1 Treatment Train Quantitative Criteria

6.4.1.1 Total energy consumption of the water reuse systems

Water reuse systems utilize various forms of energy –especially in operation and maintenance phase for the production of fit-for-purpose reclaimed water. Energy requirement can be linked to the type of treatment technology, the degree of system automation and end users' preference. Previous studies such as Venkatesh et al. (2014), Venkatesh and Brattebo (2011), Stokes and Horvath (2010), Pan et al. (2011), Merlin and Lissolo (2010) and Hellstrom (1997) have focused only on electrical energy requirement for water reclamation plants. Furthermore, these studies have been limited in providing insight into understanding the water-energy interdependent relationship commonly known as the water-energy nexus with regards to water reclamation for potable applications. In SA, WRSs are plagued with controversies and ambiguities regarding energy consumption as this significantly contribute to the operational and maintenance costs as well as the overall impact on the health of the environment. Furthermore, traditional energy estimation methods cannot easily track the differences in several forms of energy relative to activities as a resource demands operation and maintenance activities involved in water reclamation. To clarify the ambiguity regarding the different types of energy requirements and provide an unbiased comparison between WRSs, energy utilization in operation and maintenance phase of WRSs was examined.

Simple methods of calculating energy consumption fail to take into considerations other forms of energy expended with the focus mainly on electrical energy intensity. Furthermore, the study by Frank bellosa (2007) made a case for activity driven energy accounting. A detailed knowledge of the pattern of energy use is vital to energy benchmarking and management procedures (Frank bellosa 2007). Curry et al. (2012) suggests the use of energy accounting approach that measure, analyze and provide information on different energy consuming activities on a regular basis. It is essential to know where energy is utilized and the entity responsible its utilization. For the purpose of exploring opportunities for energy efficiency and substitution, a comprehensive examination of several types of energy utilized in association with the relevant activities involved is needed. Such investigation should take into consideration several forms/sources of energy and their intensity at several stages of the treatment process and the activities involved in reclaimed water production.

Hence, in this study, we develop an activity-based energy utilization (ABEU), model. This model is based on the concept of energy accounting and that energy consumption is not a function of the quantity of reclaimed water produced but instead energy utilized by several activities and processes that are necessary to perform for the production of a unit of fit-for-purpose reclaimed water. The ABEU model the different source of energy as a form of resource utilization and operational activities as well as assigning resources utilized to energy source as activities based on their use and recognizes energy utilization drivers to activities. The assumption in this study of is that energy intensity of the WRSs comes from electrical, chemical manual and mechanical energy requirements needed for the production of reclaimed water. Under this approach, multiple forms of energy usage are assigned to the treatment process and activities and the overall energy usage is obtained from a bottom-up amalgamation of the primary treatment unit processes and sub-processes as well as other energy consuming activities involved. The following steps used in this study were adopted from Ruiz-Rosa et al. (2016) four steps for activity-based cost model for the development and calculation procedures of the activity based energy intensity/utilization model:

Step 1: Identification of reclaimed water as the end product and description of its unit of measurement

Step 2: Establishing the systematic progress flow of raw product to end product and relative treatment units and activities

Step 3: Categorization and linking of factors influencing the different forms of energy consumed in the systematic progress flow of feed-water/raw product to reclaimed water/end product. Moreover, these factors can be categorized as either having a direct/indirect impact on the energy utilization objective established by the management procedures. These factors can also be termed as a fixed or variable function, with regards to their dependence on the volume of activity.

Step 4: Development of a matrix linking the different forms of energy utilized with relevant activities, as well as the between activities and the end product. Furthermore, this matrix provides a basis for estimating the energy utilized for the systematic progress flow of raw product to end product.

Step 5: Development/modification of mathematical models for evaluating each specific form of energy utilized for the transformation of raw product to end product

- **Application of steps**

Step 1: Identification of reclaimed water as the end product and description of its unit of measurement

Reclaimed water (end product): This is wastewater have undergone stringent treatment processes to meet the required standards for potable use. Wastewater is often regarded to return flow generated from activities such as laundry, flushing, bathing and light industrial activities such as cooling is considered as a renewable resource (Estevan and Naredo, 2004 and Ilemobade et al. 2009).

Step 2: Establishing the systematic progress flow of raw product to end product and relative treatment units and activities

The systematic progress flow of raw product (wastewater) to end product is the processes and activities that are involved in the transformation of raw product to end product. Wastewater subjected to treatment transforms to end product fit for potable (direct/indirect) and non-potable use. The raw product transformation to fit-for-purpose reclaimed water is the product transformation considered in this study. Sequences of activities are involved in the treatment process which can be directly/indirectly connected to the raw product transformation. These activities can be classified into (i) main activities (activities that directly affect the transformation process) and (ii) auxiliary activities (activities that are not directly involved in the transformation process but they do facilitate the main activities).

Step 3: Categorization and linking of factors

In this section, the type of energy source and different activities is defined and categorized into groups. We considered four types of energy utilized in the wastewater treatment process:

- Electrical Energy: This is the form of energy used for treatment processes/unit that requires electricity to function (e.g., pumps, agitators, clarifiers, etc.)
- Chemical energy from treatment products: Chemical energy is released/absorbed during a chemical reaction from the use of chemicals and reagents for treatment processes and activities associated with the production of end product. Examples of this chemicals and reagent include sodium hypochlorite, sulphuric acid, Sodium hydroxide, hydrogen peroxide, chlorine gas, etc.

- Manual Energy: This is a type of energy expended for performing manual activities that facilitate reclaimed water production (such as installing of packing glands, clearing of debris built-up from the feed-water intake, cleaning of the dosing-pump tanks, dosing pump strainer and dosing pump valves, etc.).
- Fuel Energy: This is the form of energy utilized by combustion of fuel (diesel/petrol) by mechanical units/ activities involved in the product transformation process.

These different groups of activities and the type of energy source utilized can (i) be linked directly thereby indicating a clear relationship between the nature of energy used and (ii) an indirect relation where the form of energy utilized affect more than one activity. In the second case, we adopt the process suggested by Alvarez-Dardet Espejo (1993) by using an energy source driver that allows for the distribution of this indirect type of energy utilized logically amongst the different activities.

Step 4: Development of a matrix linking different forms of energy utilized with relevant activities

This step entails identifying the different activities involved in reclaimed water production. This step takes into cognizance the specific type of energy used and the corresponding activity necessary to complete the transformation process. Moreover, this step also entails the developing a logical system of linking (i) energy source and activities; and (ii) energy source among activities. In both cases, the activities will be the starting point of reference.

It should be noted that where a unit value for energy requirement is assigned to a main treatment unit process/activity, the assigned unit value for energy utilized by the auxiliary activity facilitating this main activity is consolidated with the main activity energy utilization value. Once the energy utilization activity has been established, the next phase is the complete bottom-up consolidation of energy utilization features depending on the nature of such activity into the overall energy utilized for the production of reclaimed water.

The nature of energy used is defined by the fraction of the of the energy requirement element which can be quantified by utilization of a specific type of energy source. A treatment unit sub-process consolidates all energy utilization activities contributing to the production of reclaimed water. Finally, the main treatment process integrates treatment sub-unit processes which are required for the production of reclaimed water. Therefore, this proposed ABEU model will provide a bottom-up consolidation analysis for estimating the overall energy utilization as shown in Figure 6.3 . The energy utilizing activity model is expressed by an activity matrix where the source of energy utilized (E_i) relative to unit activity (i) with sub-treatment unit processes/activities (SU_i) and main treatment unit/activity process (M_i) are represented by binary values. The combination of the energy utilization activity matrix and the different forms of energy requirement models generate an activity based energy utilization matrix, where the individual cell comprises of a unitary energy requirement/consumed linked to a specific activity.

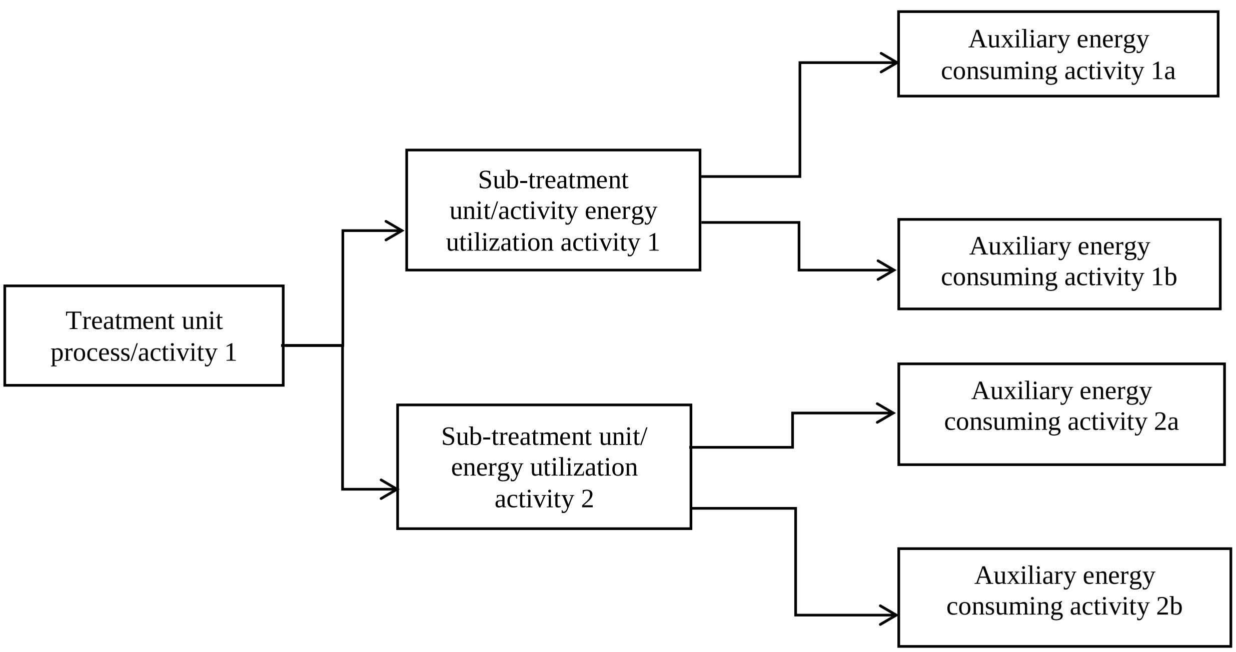


Figure 6.3: Energy consuming activities categorization

Hence, the energy utilized for the main treatment unit/activity and sub-treatment unit /activity is consolidated with that utilized by the auxiliary activity (Table 6.6).

Table 6.6: Distribution of the energy consumption of treatment units and auxiliary activities

	M_1	M_2	M_3	M_4	M_5	SU_1	SU_2	SU_3	SU_4	SU_5
E_1	E_1M_1	E_2M_2	-	-	-	-	-	-	-	-
E_2	-	-	E_2M_3	-	-	E_2SU_1		-	-	-
E_3	-	-	E_3M_3	-	-	E_3SU_1	E_3SU_2	E_3SU_3	E_3SU_4	-
E_4	-	E_4M_2	-	-	-	-	-	E_4SU_3	E_4SU_4	-

$$M_1 = \sum M_1 + E_1M_1 \quad \dots\dots\dots\dots\dots\dots \; equation\ 6.14$$

$$M_2 = \sum M_2 + E_2M_2 \quad \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.15$$

$$M_3 = \sum M_3 + E_2M_3 + E_3M_3 \quad \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.16$$

$$M_4 = \sum M_4 + E_4M_2 \quad \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.17$$

$$E_1 = \sum E_1 + E_1M_1 \quad \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.18$$

$$E_2 = \sum E_2 + E_2M_3 + E_2SU_1 \quad \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.19$$

$$E_3 = \sum E_3 + E_3M_3 + E_3SU_1 + E_3SU_3 + E_3SU_4 \quad \dots\dots\dots\dots \; equation\ 6.20$$

$$E_4 = \sum E_4 + E_4M_2 + E_4SU_3 + E_4SU_4 \quad \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.21$$

The activity based energy utilization matrix is used to resolve the links between the main and auxiliary activities.

Step 5: Development/modification of mathematical models for evaluating each specific form of energy utilized for the transformation of raw product to end product

This step involves the modification of representative mathematical equations to evaluate the form of energy utilized for performing a specific activity (main or auxiliary). After the sets of energy utilization activities and the form of the source of energy utilized have been determined, the different forms energy utilized for each unit activity is modeled by a polynomial as a function describing the energy source driver, intensity or number of drivers and unit quantity of drivers as illustrated in the modified equations from Singh et al (2012) for estimating the different forms of energy utilized by diverse activities for production of reclaimed water.

(i) Electrical Energy

The total electricity consumption by the water reclamation plant is the sum of electricity consumption of specific treatment unit processes/activities and pumping of filtrate as well as residual associated with the production of reclaimed water. Electricity consumption is calculated using equation 6.23 below:

$$E_e = EP_e + EU_e \dots\dots\dots\dots\dots\dots\dots\dots \; equation \; 6.23$$

Where

E_e = total electrical energy utilized

EU_e = total electrical energy utilized specific activities /treatment unit processes other than pumping activities

EP_e = total electrical energy utilized for pumping activities

Developing a mathematical model for estimating the energy consumed energy utilizing units such reverse osmosis unit, ultrafiltration unit, oxidation and neutralization reactors is beyond the scope of this study. However, using equation 6.24, the approximate values for the aforementioned units will be obtained using historical records of electricity consumption load and manufacturer's specification.

$$EU_i = \sum_{i=1}^{n} TU_i \, NU_i \quad \dots\dots\dots\dots\dots\dots\dots\dots \; equation \; 6.24$$

Where

EU_i = electrical energy utilized specific activity (i)/specific treatment unit process (i)other than pumping activities

TU_i = Electric consumption load of specific treatment unit (i)/activity (i)

NU_i = number of specific treatment unit (i)/activity (i)

The overall objective functions of energy utilization by these specific treatment units and activities is therefore the sum of energy consumed with respect to 1m^3 of reclaimed water produced as illustrated in equation

$$EU_e = \sum_{i=1}^{n} \frac{EU_i}{Q} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.25$$

Where

$EU_e =$ total electrical energy utilized specific activities /treatment unit processes other than pumping activities

$EU_i =$ electrical energy utilized specific activity (i)/specific treatment unit process (i)other than pumping activities

$Q\ =$ Volume of feed-water treated (m^3/day)

To evaluate electrical energy input for pumping activities, consideration was given to electrical load of pumps/motors in (KW) with motor efficiency assumed to be 80% by Fadare et. al. (2010), time in hour (h) for which the motors/pumps are operated and the total amount of treated wastewater/ reclaimed water produced according to equation 6.26 by Singh et al. (2012).

$$EP = \frac{P \times T}{Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.26$$

Where

$EP =$ the electrical energy for pumping

$T =$ operation hours (hr/day)

$Q =$ total flow of waste-water in m^3/day

$P =$ the rated power of electrical motor (kw)

However, in reality in a water reclamation plant pumping activities are carried out by several pumps for conveyance of fluid with different density such as filtrate and slurry, varying flow rates and pump heads. Therefore, in this study the energy utilized by a group of pumping units is expressed by equation 6.27.

$$P_e = \sum_{i=1}^{n} \frac{\rho_i \; g \; C_i \; H_i}{\eta_i} \quad \dots \dots \dots \dots \dots \dots \dots \dots \; equation \; 6.27$$

Where

P_e = electrical energy utilized by a group of pumping units

ρ = density of specific pumped medium i

C_i = capacity head of specific pumping unit i

H_i = head of specific pumping unit i

η_i = efficiency of specific pumping unit i

g = acceleration due to gravity

Therefore, the unit energy consumption P_e of the pumping unit in the process of pumping 1m3 of reclaimed water is obtained using equation 6.28

$$P_e = \frac{9.81}{3.6Q} \sum_{i=1}^{n} \frac{H_i C_i T_i}{\eta_i} \dots \dots \dots \dots \dots \dots \dots \dots \; equation \; 6.28$$

Where,

T_i is the duration of operation of each pumping unit per day (hr/day) and Q = total flow of waste-water in m^3/day

Therefore, the total electricity consumption for the production of reclaimed water is estimated using equation 6.29

$$E_e = \frac{9.81}{3.6Q} \sum_{i=1}^{n} \frac{H_i C_i T_i}{\eta_i} + \sum_{i=1}^{n} \frac{EU_i}{Q} \dots \dots \dots \dots \dots \dots \dots \dots \; equation \; 6.29$$

(ii) Estimation of Chemical Energy

Chemical energy is calculated by estimating the standard enthalpy (heat) of reaction (ΔH) of the chemicals during a reaction. , Singh et al (2012) used equation 6.6 to estimate chemical energy (EC) in KWh/m^3 for a wastewater treatment plant

$$EC = \frac{n[\Sigma \Delta HP \; - \; \Sigma \Delta HR]}{Q} \times 0.000278 \dots \dots \dots \dots \dots \dots \dots \dots \; equation \; 6.30$$

Where,

n = the number of moles moles (mol/day),

0.000278 = the conversion factor from KJ to KWh,

ΔHP = the enthalpy (heat) of formation of products (KJ/mol), and

ΔHR = the enthalpy (heat) of formation of reactants (KJ/mol).

Q = Volume of wastewater treated (m^3/day)

However in this study, chemical used for treatment and their respective quantities for treatment will be using the equation 6.31 as follows:

$$C_e = 2.78 \times 10^{-4} \sum_{i=1}^{n} D_I Q \; [\Delta HP_i - \Delta HR_i] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.31$$

Where,

2.78×10^{-4} = the conversion factor from KJ to KWh,

ΔHP_i = the enthalpy (heat) of formation of product for specific activity (KJ/mol),

ΔHR_i = the enthalpy (heat) of formation of reactant for specific activity (KJ/mol).

Q = Volume of feed-water treated (Ml/month)

D_i = chemical dosing frequency for specific activity (g/m^3)

(iii) Estimation of Fuel Energy (Mechanical Energy)

Singh et al (2012) used equation 6.32 to estimate in Mechanical Energy (EF) in KWh/m^3 for a wastewater treatment plant

$$EF = \frac{15.64D}{Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.32$$

Where:

15.64 = the unit energy value for diesel in KWh/l (Devi et al. 2007)

D = the amount of diesel consumed in l/day.

Q = Volume of wastewater treated (m^3/day)

However in this study the equation 6.33 used is as followed:

$$F_e = \frac{15.64}{Q} \sum_{i=1}^{n} V_i \; NR_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.33$$

Where:

V_i = volume of diesel consumed for specific activity

NR_i = number of units/frequency of specific activity

15.64 = unit energy value for diesel in KWh/l (Devi et al. 2007)

Q = Volume of produced (m^3/day)

(iv) Estimation of manual energy

Manual energy is required for different activities such as operating the switches, opening/closing of the sludge valves, cleaning of tanks and operating valves to remove the sludge from tanks etc. Manual energy consumption is a function of gender of labor and the nature of activity (Table 6.7).

Table 6.7: Human power equivalent (E) in kW (WHO 1985)

Input	Male	Female	Activities
Light	0.13	0.10	Switch on/off pumps, maintain the log-book, check motor temperature
Moderate	0.14	0.11	Open/close the sludge drain valve, operation of valves for backwashing
Heavy	0.54	0.44	Prepare the chemical solution for dosing, fill the chemical solution in the dosing tank, collect the dried sludge in containers (gunny bags)

Based on these considerations, Singh et al (2012) used equation 6.34 to estimate manual energy for a wastewater treatment plant.

$$E_m = \frac{\sum_{i=0}^{i=n} \sum_{j=0}^{j=m} E_{IJ} \, N_{ij} \, T_{ij}}{\mathrm{Q}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.34$$

Where,

E_m = the manual energy in kWh/m^3,

$n =$ the number of nature of activities (light, active and heavy),

$M =$ the number of gender (male, female), E the human power equivalent (kW),

$M =$ the number of persons engaged in an activity and

$T =$ the total time devoted in the activity (h/day).

Q = Volume of wastewater treated (m^3/day)

However in this study, the equation 6.35 used is as follows:

$$M_e = \frac{\sum_{i=0}^{i=n}\sum_{j=0}^{j=m} \left(EM_{ij}NM_{ij} + EF_{ij}NF_{ij}\right) F_{IJ}\, D_{ij}}{Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.35$$

Where:

M_e = Manual energy (kWh/m^3),

D_{ij} = Duration of specific activity (mins),

F_{IJ} = Frequency of specific activity,

NF_{ij} = Number of female performing specific activity,

EF_{ij} = Female human power equivalent for specific activity (KW),

EM_{ij} = Male human power equivalent for specific activity,

NM_{ij} = Number of male performing the specific activity,

Q = Volume of feed-water treated (m^3/day)

Therefore, equation 6.36 is used for estimating total energy consumption of the water reuse system EC_T is

$$EC_T = \frac{9.81}{3.6Q}\sum_{i=1}^{n}\frac{H_iC_iT_i}{\eta_i} + \sum_{i=1}^{n}\frac{EU_i}{Q} + 2.78\times 10^{-4} + \sum_{i=1}^{n} D_IQ\ [\Delta HP_i - \Delta HR_i]$$
$$+ \frac{15.64}{Q}\sum_{i=1}^{n} V_i\ NR_i$$
$$+ \frac{\sum_{i=0}^{i=n}\sum_{j=0}^{j=m} \left(EM_{ij}NM_{ij} + EF_{ij}NF_{ij}\right) F_{IJ}\, D_{ij}}{Q} \ldots \; equation\ 6.36$$

The total energy utilized will be balanced quantitatively against energy (kWh) from the production of one cubic meter reclaimed water.

- **Results and Discussion: application of the ABEC model proposed**

This study aims to perform an empirical application of the ABEU model suggested in the previous section. The information used for the analysis was supplied by two water reclamation plants in Mpumalanga province, in SA. The estimation process was based on the sequence of steps proposed in the previous section as well.

Step1*: Identification of reclaimed water as end product and description of its unit of measurement*

The previous section has established that the end product considered in this study is reclaimed water suitable for potable applications. Using the proposed unit of measurement, water reclamation plants A and B produced an average of 19295 m^3 and 14235 m^3 per day of reclaimed water respectively.

Step 2: *Establishing the systematic progress flow of raw product to end product and relative treatment units and activities*

The systematic transformation of the feed-water (influent) to end product (reclaimed water/effluent) is directly related to the pollutant removal efficiencies of the different stages of treatment. Table 6.8 shows an example of the classification of the treatment stages and the types of activities (i.e. main or auxiliary activity). The analysis of the transformations for plant A consists of overall of thirty-nine energy-consuming activities, seven of which are primary energy consuming activities and thirty-two auxiliary energy-consuming activities (Appendix 5). For plant B, a total of thirty-five energy-consuming activities, seven are main energy-consuming activities, and twenty-eight are auxiliary ones (Appendix 6).

Furthermore, for the main energy consuming activities, there are three treatment stages (primary, secondary and tertiary) and one final step for product polishing (disinfection). Different treatment products (chemical and reagents) and sources of energy are utilized in the treatment processes involved in water reclamation. At this step, the set of activities involved in the water reclamation processes are identified in relation to the different forms of energy required for the total transformation of wastewater to finished product.

Step 3: *Categorization and linking of factors*

As stated earlier, the four forms of energy considered in this study utilized for the transformation process of feed-water to reclaimed water are electrical, chemical, manual and mechanical. These energy sources are considered for the production of an average volume of 19295 m^3 and 14235 m^3 per day of reclaimed water from water reclamation plants A and B respectively.

Step 4: *Development of a matrix linking energy utilized with relevant activities*

By connecting the appropriate form of energy consumed with a specific activity, the nature (which can be indirect/direct, variable/fixed) of the specific type of energy consumed in performing the associated activity is well-defined. We define energy utilization drivers as the factors that reflect the causes that influence the amount of energy utilized.

Table 6.8: Classification of water reclamation treatment stages, processes and energy utilization activities

MAIN ACTIVITIES
Primary treatment
Oxidation and Neutralization (reactors)
Agitators
Precipitation reactors
Clarification (Clarifiers)
Secondary treatment
Ultrafiltration
Tertiary Treatment
Reverse osmosis
Disinfection
Chlorination: (Chlorine Gas)
Chlorine reduction in filtrate: (SMBS)
pH neutralization after chlorination: (Carbon Dioxide)
AUXILIARY ACTIVITIES
Pre-treatment activities before partially treated effluent goes to RO (Antiscalant)
Checking pH/flow readings and record
Conducting of jar test for determining the appropriate dosage of the chemicals
Taking of samples in the agreed sampling points at agreed intervals
Backwashing of the filters
Preparing working solutions for test in the laboratory
Changing of chemical gas cylinders
Installation of packing glands
Clearing of debris built-up from feed-water water intake.

Table 6.89 shows a partial set of description of energy utilization driver and the factors that influences these drivers among activities. This information permits the recognition of factors that are needed in lesser quantity than the estimated ones and as a result, identifies if idle energy sources are being maintained. A detailed table with the overall energy utilized associated with each form of energy as well as energy drivers for each activity is included in the appendix of this study. Furthermore, the unitary energy utilized per driver allows the dissemination of the overall quantity of each factor among the different activities according to the form of energy utilized by individual activities is calculated in step 5.

Step 5*: Development/modification of mathematical models for evaluating each specific form of energy utilized for the transformation of raw product to end product*

At this stage, mathematical equations are employed to estimate the overall form of the specific energy utilized for a particular activity. In some cases, conversion factors are used estimate the value of energy utilized in kwh/m^3.

Table 6.9 Activity drivers, main and auxiliary activities descriptions (extracted from appendix 6)

Concept and activity description	Description of energy utilized	Energy utilization activity drivers					
Main Activities	**Electrical energy**	**Unit energy utilization kWh/m3**	**Number of units**	**Duration of operation per day**	**-**	**-**	**Volume of reclaimed water m^3/day**
Agitators(equipment)	kWh/m^3	0.0167	30	24	-	-	19295
Disinfection	**Chemical energy**	**g/m3 of product**	**Number of moles**	**Molar mass (gram/mol)**	**Heat of reaction**	-	
Neutralization of filtrate (NaOH)	kWh/m^3	4.5	0.11	39.997	42.9	-	19295
Auxiliary Activities							
Chemical treatment activities and products	**Chemical energy**	**g/m^3 of product**	**Number of moles**	**Molar mass (gram/mol)**	**Heat of reaction**	-	
Pre-treatment activities before effluent goes to RO (Antiscalant)	kWh/m^3	6.47	0.11	57,04	134.12	-	19295
Pumping	**Electrical energy**	**Pump operation hours per day**	**Abstracted power (kw)**	**Pump flow rate (m^3/hr)**	**Pump head (m)**	**Number of pumping units**	
Ultrafiltration feed pumps	kWh/m^3	24	29.19	560	24	6	19295
Fuels	**Fuel energy**	**Litres/day**	**Number of units**	-	-	-	
Diesel generator	kWh/m3	4.5	1	-	-	-	19295
Labor (Operation and maintenance)	**Manual energy**	**Number of hours**	**Nature of activity**	**Frequency of activity**	**Gender**	**Number of people performing activity**	
Installation of packing glands	kWh/m^3	2	light	Four times/day	Male & Female	2	19295

Furthermore, the unit energy utilized per driver allows the dissemination of the overall amount of each factor that affects energy utilization drivers with respect to the energy intensity of activity. Spreadsheets in appendices 6&7 show that the overall daily energy utilized in quantitative units in relation to individual energy source as well as the energy utilization drivers attributed to each activity.

After identifying the different activities involved in the treatment process and the form of energy utilized for these activities, the energy utilized for these activities were estimated using the equations in the previous section. The energy utilized for relevant auxiliary activities were distributed among the main activities. These auxiliary activities directly support the main activities with the objective aimed at grouping all forms of energy used for auxiliary activities within each relevant main activity. Also, the activity based energy utilization matrix was employed to resolve the relationship between the auxiliary activities that are dependent on other auxiliary activities. With the goal of estimating the overall energy utilized for the main activities, several energy utilization activity drivers such as the frequency/resources required for that activity per day are shown in Table 6.9. These energy utilization activity drivers are dependent on the volumetric capacity of the water reclamation plant (i.e. the volume of feed-water treated per day) and the characteristics of the feed-water (Table 6.9).

For plant A, the energy utilized by primary, secondary, tertiary and disinfection treatment activities are 1.9026kWh/m^3, 0.7701kWh/m^3, 1.812kWh/m^3 and 0.0453kWh/m^3 respectively. From the analysis of the results, it can be deduced that energy utilized by primary treatment activities contribute the most significant share of 42 %, tertiary treatment activities 40 %, secondary treatment activities 17% and disinfection treatment activities 1% to the overall energy utilized for the production of 19295 m^3 of reclaimed water per day. For plant B, the energy utilized by primary, secondary, tertiary and disinfection treatment activities are 0.953kWh/m^3, 0.2861kWh/m^3, 0.928kWh/m^3 and 0.021Wh/m^3 respectively. From the analysis of the results, it can be deduced that energy utilized by primary treatment activities contribute the most significant share of 43.5 %, tertiary treatment activities 42.5 %, secondary treatment activities 13% and disinfection treatment activities 1% to the overall energy utilized for the production of 14235 m3 of reclaimed water per day.

Table 6.10 and Table 6.11 illustrate the distribution of the overall energy utilized among the main and auxiliary activities for plant A and Plant B respectively. For plant A, Table 6.10 indicates that 54% of energy utilized is for main activities (i.e. treatment unit processes) while 46% is utilized for auxiliary activities. The energy requirement for pumping operations makes up 62% of the overall energy used for auxiliary activities which also high in comparison with each main activity. The energy utilized for pumping is quite high for plant A, probably due to the geographical location features of the case study site. Walski (2012) alluded to this fact that energy expended on pumping activities can be significantly high due to the specific design characteristics of the water reclamation plant in relation to land topography. For plant B, Table 6.11 shows that 66% of the energy utilized by main activities while 34% is utilized by auxiliary activities facilitating the main activities.

Table 6.10: Distribution of the overall energy utilized among the activities for Plant A

Main activities	**kwh/m^3**	**%**	**Auxiliary activities**	**kwh/m^3**	**%**
Primary treatment	**1**	41	Primary treatment	**0.732**	35
Secondary treatment	**0.43**	18	Secondary treatment	**0.0041**	0.22
Tertiary treatment	**1**	17.70	Tertiary treatment	**0.008**	0.38
Disinfection	**0.006**	0.30	Analysis and test	**0.0014**	0.10
			Pumping	**1.3**	61.9
			Maintenance	**0.052**	2.4
Sub total	**2.436**	**54**		**2.09**	**46**
Total	**4.53**				

Table 6.11: Distribution of the overall energy utilized among the activities for Plant B

Main activities	**kwh/m^3**	**%**	**Auxiliary activities**	**kwh/m^3**	**%**
Primary treatment	**0.5**		Primary treatment	**0.453**	61.369
Secondary treatment	**0.18**		Secondary treatment	**0.0061**	0.826
Tertiary treatment	**0.75**		Analysis and test	**0.00006**	0.008
Disinfection	**0.012**		Pumping	**0.27**	36.577
			Maintenance	**0.009**	1.219
Sub total	**1.44**	**66**		**0.74**	**34**
Total	**2.18**				

As shown in Table 6.12, the overall energy utilized by plant A and B are 4.53kWh/m^3 and 2.1803kWh/m^3 for the production of an average of 19295 m^3 and 14236 m^3 of reclaimed water per day respectively. Both values are much higher in comparison with the energy utilized by convention wastewater treatment presented by stokes and Horwath (2010) and Singh et al. (2012). According to Yifan Gu et al. (2017), advanced treatment processes for the production of reclaimed water for potable applications are highly energy intensive with values ranging from 0.39 up to 3.74 kWh/m^3. It is commensurate with the result obtained in this study for plant B. Yifan Gu et al. (2017) only considered electrical energy, hence, other forms of energy account for the additional 0.806 kWh/m^3 in the result obtained for plant A. Guimet et al. (2010) reiterated that energy requirement varies considerably among water reclamation plants due to the characteristics of feed-water, required reclaimed water quality and plant size.

Some findings are significant from the point of view of energy management, energy utilization drivers, and activities. For plant A, the electrical form of energy has the most substantial portion (82%) of the four types of energy sources (Table 6.12). For plant B, the electrical form of energy has the most considerable portion of 66% of the forms of energy under consideration (Table 6.12). Singh et al. (2012) stated that electrical energy utilization varies by a factor of 1.6 (as this is evident from literature) depending on the treatment technology, size and degree of automation of the plant. The operations of Plant A and B are highly automated as reflected in the result obtained for manual energy intensity as shown in Table 6.12. Energy utilized for manual activities constitute 0.002% and 0.0003% of the overall energy utilized by plant A and plant B respectively. The overall chemical energy utilized by plant A and B are 0.76kWh/m^3 and 0.46kWh/m^3 respectively. This implies that chemical energy makes up 17% and 21% of the overall energy utilized by plant A and plant B respectively; hence, it cannot be considered to be insignificant.

Table 6.12 Overall forms of energy utilization by water reclamation plants

	Plant A		**Plant B**	
Form of energy	**kwh/m^3**	**%**	**kwh/m^3**	**%**
Electrical energy	3.73	82	1.7	78.09
Chemical energy	0.76	17	0.45	20.6
Fuel energy	0.044	0.97	0.03	1.3
Manual energy	0.002	0.04	0.0003	0.01
Total	4.53		2.18	

The overall mechanical energy (fuel energy) utilized by plant A and plant B respectively are 0.044kWh/m^3 and 0.03kWh/m^3 respectively (Table 6.11). Although these values are relatively low, mechanical energy consumes 0.1% and 1% of the overall energy utilized by plant A and B respectively.

- **Conclusion**

In this study, we explored the activity based concept for the estimation of energy utilized for the production of reclaimed water for potable application. This approach permits the use of a set of control parameters for activity drivers and energy utilization drivers which enable the optimum management of this procedure. This approach quantifies from the perspective of the different forms of energy utilized and the amount of energy utilized for a specific activity. This implies that vital information could be obtainable when managing the activities involved in the production reclaimed water thereby contributing positively to the efficiency of the decision-making process. Furthermore, this approach could enhance compiling historical informative data over-time which can be of tremendous assistance in the comparative assessment of energy intensity of different activities and processes at different period of production. Based on the result of this study, it can be said that the high energy intensity values obtained from plant A and B can be attributed to the use of energy-intensive technology such as membrane technologies (reverse osmosis and ultrafiltration units), agitators, pumps and most importantly chemical reagents due to the type of feed-water (mine water). However, there is need to support this generalization by analyzing several treatment technologies and constituent of concern in feed-water in different regions across the globe.

6.4.1.2 Operation and Maintenance Cost of Water Reuse Systems

Managing operating and maintenance costs is imperative to the economic sustainability of WRSs over time (Caballer and Guadalajara, 1998; Sipala et al. 2003; Chen and Wang, 2009; Hernandez-Sancho et al. 2011). However, several cost analysis techniques are mainly designed to meet reporting and financial accounting requirements thereby limiting their abilities and applicability for decision making and continuous improvement. In an effort to address the perception that WRSs have a high (unsustainable) cost/benefit ratio which calls to question their economic viability, it is imperative to emphasize the need for evolving techniques for assessing operation and maintenance cost of WRS operations. Berbeka et al. (2012) suggested that more work needs to be done to provide in-depth analysis of significant cost drivers associated with water reclamation processes for a better understanding of the sensitivity of relevant cost functions.

Activity-Based Costing (ABC) can be used to improve the accuracy of cost management information as well as further control on operational costs of systems (Botin and Vergara, 2015; Ruiz-Rosa et al. 2016). Studies by Caballer and and Guadalajara (1998); (Sipala et al (2003); Chen and Wang (2009); Zessner et al. (2010) ; Berbeka et al. (2012) have employed the use of cost analysis model that use arbitrary techniques to link cost with product resulting in inaccurate information (Ruiz-Rosa et al. 2016). Ruiz-Rosa et al. (2016) developed a cost analysis model based on the ABC methodology to address the problems with these previous studies. However, the study by Ruiz-Rosa et al. (2016) was limited in addressing the variable nature of cost with pricing, operational constraints such as capacity expansion within the scope of operational management. Furthermore, investigating operation-related decisions with rigid constraints illustrates the practicality of variable costing integrating the impacts of bottleneck activity within the economical scope of operation and management. In this study, reclaimed water/filtrate is regarded as product that requires production cost information for decision making process. Differing from the previous researches, this study aims to develop an integrated cost analysis model (ABC and mathematical programming approaches) for assessing operation and maintenance cost of WRSs. The resources utilized and activities that are involved in the operation and maintenance of phase of WRSs are incorporated into ABC model. The mathematical programming approach was used to incorporated features such as capacity expansions and price elasticity into the ABC model.

The role that mathematical programming plays is critical in understanding the impact of the environment on cost efficiency measures to acquire the needed information about real-world scenarios such as the assessment of operation and maintenance costs of water reclamation plants. In order to address constraints and challenges associated with assessing operation and maintenance cost of WRSs, this study develops a mathematical programming model for estimation of operation and maintenance cost regarding water reclamation for potable applications. This study also incorporates factors such as capacity expansion, the elastic nature of price and changing feed-water qualities into the ABC analysis model to enhance efficient and effective cost management to encourage long-term sustainability as part of the decision-making process.

Operation and maintenance costs play a vital role in the day to day expenditure for the operation of water reclamation plants. Operational expenditures represent costs incurred due to the day-to-day running of water reclamation plants after the completion of the construction and commissioning phases. Operational expenditure is an on-going expense that is mainly accrued on a daily basis as long as the plant is operational. The significant factors that contribute to the cost of operation and maintenance phase WRSs are discussed below. The operation and maintenance expenditures considered in this study consists of energy, chemicals, maintenance, labor and residual management and disposal as described below:

- **Energy** – Energy utilization is one of the major contributors to the operation cost of a water reuse system as almost all processes from feed-water transformation to filtrate/reclaimed water, as well as pumps, are directly or indirectly dependent on electricity.
- **Chemicals and reagents** – Chemicals and reagents are essential commodities utilized for various treatment processes such as flocculation, coagulation, disinfection, and stabilization, etc. chemicals and reagents utilization are largely dependent on the feed-water quality, operating strategy and selected treatment train technology and the recycled water quality required by the end users. The cost of chemicals and reagents depends on the characteristics of the feed-water

and discharge norm, correct dosing, and the selected chemical and purchasing deals.

- **Maintenance** – Maintenance is an imperative activity carried out to ensure the needed proper functioning and damage prevention or control to minimize the chances of system breakdown. The management planning and strategy of maintenance activities play a vital role in the effective and efficient performance over the service life of the system. Maintenance costs include repair of membranes to improve integrity, major or minor parts replacements such as pumps, inspection and maintenance personnel charges, consumable materials (filters), etc.
- **Labor** – This entails variable and fixed remuneration or monetary payment of permanent and temporary personnel/staffs required to operate and maintain the water reclamation plant. These personnel/staffs are saddled with the responsibility of ensuring that the plant functions efficiently and effectively. Furthermore, the staffs ensure that the required water quality is attained and compliance with the regulatory standard are met and maintained. The size of the reclamation plant, level of automation and selected technology are major factors that significantly affect the cost of labor/personnel of a water reuse system.
- **Residue management and disposal** – Sludge is a by-product of the physical and chemical treatment processes involved in reclaimed water production. As a result of this, the sludge stream tends to contain pollutants removed from the feed-water stream. However, sludge also contains nutrients (e.g., nitrogen and phosphorous) that can be used for soil enrichment and building purposes. Any approach employed for sludge treatment and disposal must be cost-effective and not detrimental to the environment as well. Disposal of sludge is largely dependent on the constituent of concern in the sludge meeting the allowable disposal requirement standards, potential market value and ambient conditions.

In this study, the assumptions highlighted below were taken into consideration and integrated into the cost analysis model:

- The cost associated with the operation and maintenance phase of water reuse systems include energy cost, chemical cost, maintenance cost, cost of labor and cost of residue management and disposal.
- Decision makers have access to accurate operation and maintenance cost information from existing systems which can allow them to formulate policies which will encourage, effective, efficient and sustainable operations. Each water reuse system has its operation and maintenance costs management strategies; hence, costs are not influenced by short-term cost variations.
- Residue and disposal management for water reuse systems enhance sustainability and results in less environmental pollution. Operators and managers of water reuse systems need adhere to sludge disposal regulations and to establish a cordial relationship with government regulatory agencies and community allowing for room for constructive conversation on sludge/bio-solid disposal and reuse. Operators and managers of WRS place importance on environmental protection and corporate responsibility, hence, the residue management and disposal cost is calculated for the operation and maintenance phase of water reclamation processes, increasing treatment bye-product and pollutants in treatment bye-product as these will affect disposal medium, cost of disposal as well as reuse potential.
- The cost of chemicals used for the production of reclaimed water in operation and maintenance processes are fixed within an appropriate range over a short period of time. The direct cost of labor for the operation and maintenance phase of water reuse system can be increased as a result of working overtime or additional work shift and by employing short-term labor at a stipulated remuneration rate for a short period of time. Substitution of resources (e.g., replacing labors with machine hours) is not considered in this cost analysis model.
- In the operation and maintenance phase of water reclamation processes, the activities involved are categorized into activity drivers and resource drivers with regards to the operation and management strategies of the system's ABC plan.

According to the assumptions described above, cost linked with the operation and maintenance phase of water reuse systems include energy cost, chemical cost, maintenance cost, cost of labour and cost of residue management and disposal. The cost characteristics constraints cover changes in feed-water qualities, capacity expansion, cost of unplanned maintenance, changes in pollutant concentration in sludge/bio-solids, sludge disposal costs.

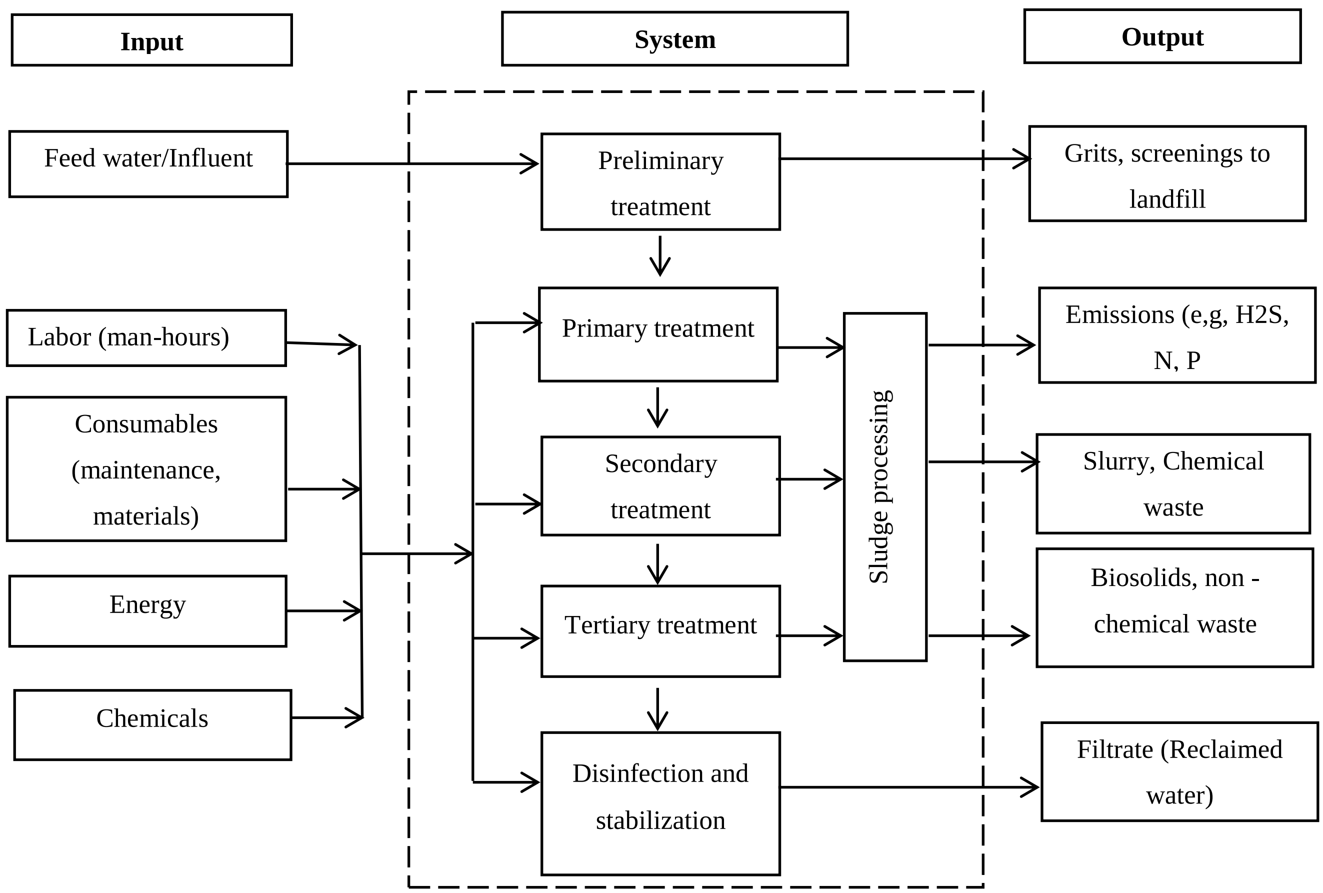


Figure 6.4: Block diagram for water reclamation processes

These are factored into 0-1 mixed integer programming (0-1 MIP) cost analysis model, then, equations of models for estimating operation and maintenance costs in the operational phase water reuse systems. The operation and maintenance cost estimation using cost analysis model is described as follow:

$$OMC_T = \ TC + TLC + TE + SDC_t + TMC \quad \dots \dots \dots \dots \dots \dots \dots \ equation\ 6.37$$

Where,

$OMC_T =$ total operation and maintenance cost (Zar/m^3); $TC =$ total cost of chemicals (Zar/m^3); $TLC =$ total cost of labor (Zar/m^3); $TE =$ total energy cost (Zar/m^3); $SDC_t =$ total cost of residual and waste disposal (Zar/m^3); $Q =$ volume of reclaimed water produced (Ml/month); $TMC =$ total maintenance cost (Zar/m^3)

- ***Total Cost of Chemical Consumed***

$$TC = \sum_{c=1}^{n} \frac{UC_c\ (D_c \times Q)}{Q \times 1000} \ \dots \dots \dots \dots \dots \dots \dots \dots \ equation\ 6.38$$

Where TC is the total chemical cost for operation and maintenance of the water reuse system (Zar/m^3); UC_c is the unitary cost of chemical (Zar/kg); Q is the volume of reclaimed water produced and D_c chemical dose (g/m^3).

[Chemical requirement constraints]:

$$\sum_{i=1}^{n} CR_i + \sum_{r=1}^{g} CR_r\ Q_r \geq 1 \dots \dots \dots \dots \dots \dots \dots \dots \ equation\ 6.39$$

$$\sum_{r=1}^{g} Q_r = 1 \dots \dots \dots \dots \dots \dots \dots \dots \ equation\ 6.40$$

Where CR_i is the quantity of chemicals required for treating the allowable feed-water quality or feed water capacity, Q_r is a special ordered sets of type 1 (SS1) set of 0/1 variables, with one variable a non-zero value. When $Q_r = 1$, this shows that the quantities of chemicals required for the treatment processes will increase to the rth level, i.e. CR_r quantities.. In this study regards the cost of chemical linked with operation and maintenance treatment processes as variable entity (Figure 6.5). Hence, the chemical cost is characterized with a stepwise function associated with different chemical requirements.

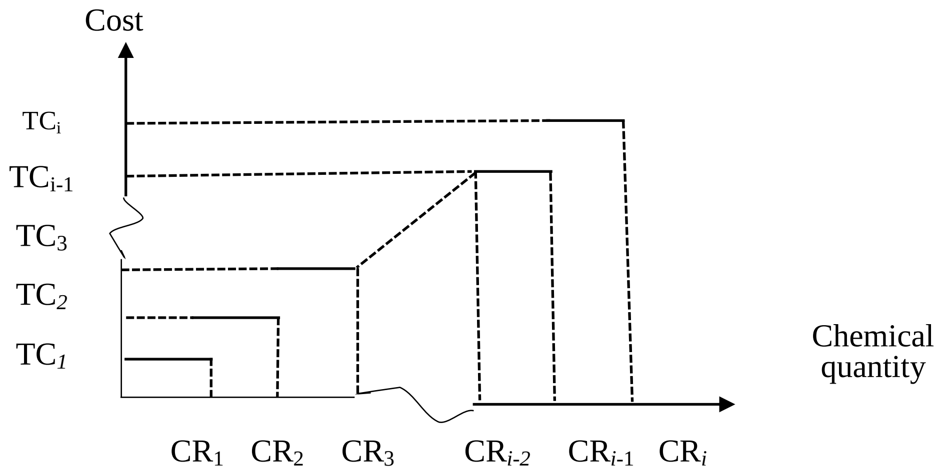


Figure 6.5: Chemical cost

The overall cost of chemicals for the treatment process is TC_1 for the current feed-water quality/capacity of CR_1 chemical requirement quantities. If the water reuse system requires an increase in chemical requirements $CR_2, CR_3, \ldots, CR_i$, the total chemical cost will be increased to $TC_2, TC_3, \ldots, TC_i$, respectively. Equations 6.39 and 6.40 represent the constraint sets associated with the cost of chemicals. Let CR_i represent the required quantity of chemical for treatment process allowable for a specific feed-water quality/feed-water capacity for a water reuse system, where $(Q_0, Q_1, \ldots, Q_r)$ is a SS set of 0-1 variables with one variable being a non-zero value (Tsai et al. 2014). The chemical quantity must be increased to *d*th quantity when $Q_d = 1 (d \neq 1)$, with an increase in chemical quantities doses/increase in flow-rate of feed-water.

- ***Total Labor Cost***

$$TLC = LC_1 + (LC_2 - LC_1)u_1 + (LC_3 - LC_1)u_2 \ldots\ldots\ldots\ldots \; equation\; 6.41a$$

$$LC = \frac{AL_C \times \sum LH_n}{Q \times 1000} \ldots equation\; 6.41b$$

Where AL_C is the average cost of labour (Zar/hr); $\sum LH_n$ is the summation of the number of hours (shifts)/month worked by all labour personnel [labor cost constraints]:

$$TLH = [LH_1 + (LH_2 - LH_1)u_1 + (LH_3 - LH_1)u_2] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.42$$

$$u_0 - \mu_1 \leq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.43$$

$$u_1 - \mu_1 - \mu_2 \leq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.44$$

$$u_2 - \mu_1 \leq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.45$$

$$u_0 + u_1 + u_2 = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.46$$

$$\mu_1 + \mu_2 = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.47$$

Where LH_1 represents the required labor hours for operation of water reuse system; LH_2 is the overall labor hours due excess work shifts or overtime by personnel as a result of operational changes as result of feed-water quality, capacity of plant and level of automation of plant changes. LH_3 is the overall fixed hours of labor due to excess work shifts by employing more personnel to work on a time-rate basis. A SS1 set of 0/1 variables are given as μ_1 *and* μ_2 with one variable a non-zero value. A special ordered set of type 2 (SS2) positive variables are represented with u_0, u_1, u_2 with possibly two adjacent variables a non-zero value.

We assume that the costs of labor for a water reuse system can increase due to increase due to working extra shifts, working overtime, and employing extra personnel on a time-rate basis. Figure 6.6shows the total fixed direct labor cost conditions with the actual fixed direct labor cost divided into optional and mandatory labor hours.

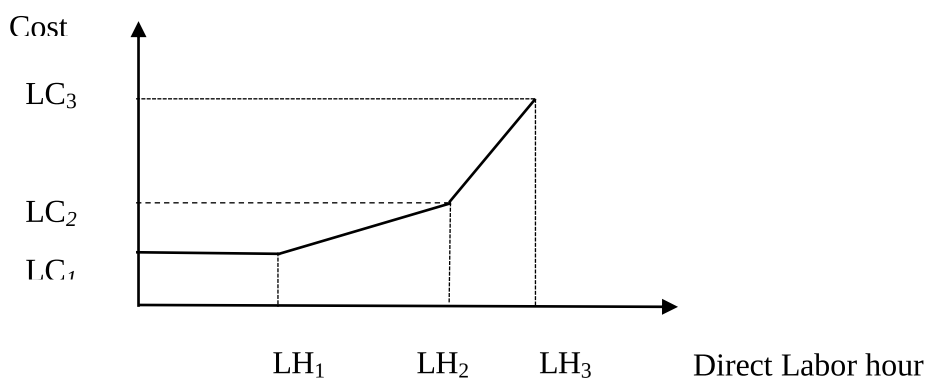


Figure 6.6: Fixed direct labor cost

The required fixed labor hours LH_1, is associated with a fixed cost denoted by LC_1 under mandatory conditions. If the fixed direct labor hours increases to LH_2 and LH_3 , these implies the overall fixed direct labor cost of LC_2 and LC_3 respectively. Therefore, the total fixed direct labor costs for optional conditions are given by $(LC_2 - LC_1)u_1 + (LC_3 - LC_1)u_2$. The constraints associated with labor hours are represented by equations 6.43 – 6.47. TLH represents the total labor hours for operations of water reclamation plant/reuse system. In equations 6.43 – 6.47, (μ_1 , μ_2) is a SS1 set of 0-1 variables with only one variable a non-zero value; (u_0, u_1, u_2) is a SS2 set of positive variables with a maximum of two adjacent variables a non-zero value (Tsai et al. 2014).

For example, if $\mu_1 = 1$, then $\mu_2 = 0$, $u_0 \le 1, u_1 \le 1, u_2 = 0$ and $u_0 + u_1 = 1$. This implies that the total labor hours required is $LH_1 + (LH_2 - LH_1)u_1$, hence the water reclamation plant with require extra working hours/overtime work. However, if $u_0 = 1$, then $u_1 = u_2 = 0$; which implies that extra working hours/overtime work is not needed. Furthermore, if $\mu_1 = 0$, then $\mu_2 = 1$, $u_0 = 1, u_1 \le 1, u_2 \le 1$ and $u_1 + u_2 = 1$. Therefore, the total labor hours required can be represented by $LH_1 + (LH_2 - LH_1)u_1 + (LH_3 - LH_1)u_2$. This implies that the operations of the water reclamation plants will require extra working hours/overtime and additional personnel/labor.

- ***Maintenance cost***

$$TMC = \sum_{i=1}^{n} \frac{NM_i MC_i}{Q \times 1000} \dots\dots\dots\dots\dots\dots\dots \; equation\ 6.48$$

Maintenance cost constraints

$$NM_t = NM_{1\gamma_1} + NM_{2\gamma_2} + NM_{3\gamma_3} \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.49$$

$$MC_t = MC_{1\gamma_1} + MC_{2\gamma_2} + MC_{3\gamma_3} \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.50$$

Where NM_t is the total cost of maintenance sessions/activities (zar), $\delta_0, \delta_1, \delta_2, \delta_3$ a SS1 set of 0/1 variables, with only one variable having non-zero value and $\gamma_1, \gamma_2, \gamma_3$ a SS2 set of positive variables, with a maximum of two adjacent variables, in the given set order can have a non-zero value.

Equations 6.51-6.56 represent the constraints associated with maintenance cost and number of maintenance sessions/activities. NM_t represents the total number of maintenance sessions/activities performed for the production of reclaimed water. The cost of each possible and relevant maintenance activity for water reclamation plant is considered essential with regards to whether to or not to execute this activity.

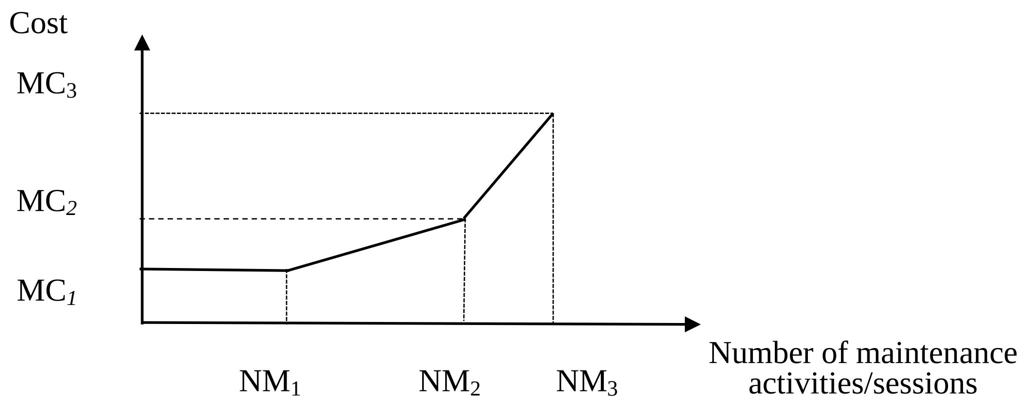


Figure 6.7: Maintenance cost

As shown in Figure 6.7, the total number of maintenance sessions/activities is depicted by a piecewise linear function composed of three sections with different cost estimate. In equations 6.53 - 6.58 $(\delta_1, \delta_2, \delta_3)$ is a SS1 set of variables with only a positive value, $(\gamma_1, \gamma_2, \gamma_3)$ is a SS2 set variables with positive values with not more than two that are adjacent variables (Tsai et al. 2014).

$$\gamma_0 - \delta_1 \leq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.51$$

$$\gamma_1 - \delta_1 - \delta_2 \leq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.52$$

$$\gamma_2 - \delta_2 - \delta_3 \leq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.53$$

$$\gamma_3 - \delta_3 \leq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.54$$

$$\gamma_0 + \gamma_1 + \gamma_2 + \gamma_3 = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.55$$

$$\delta_1 + \delta_2 + \delta_3 = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.56$$

The first segment indicates that if $\delta_1 = 1(\delta_2, \delta_3 = 0)$, then $\gamma_0 \leq 1 : \gamma_1 \leq 1 : \gamma_2 \leq 0 : \gamma_3 \leq 0$ and $\gamma_0 + \gamma_1 = 1$. Thus, the number and cost of maintenance sessions/activities are $NM_{1\gamma_1}$and $MC_{1\gamma_1}$respectively. At this point, it means that $NM_{1\gamma_1}, MC_{1\gamma_1}$ is the linear amalgamation of (0,0) and (NM_1, MC_1) in the absence of any unscheduled/unplanned maintenance activity.

Assuming that $\delta_2 = 1(\delta_1, \delta_3 = 0)$, then $\gamma_0 \leq 0 : \gamma_1 \leq 1 : \gamma_2 \leq 0 : \gamma_3 \leq 0$ and $\gamma_1 + \gamma_2 = 1$ as illustrated in the second segment. Thus, the number and cost of maintenance activities are $NM_{1\gamma_1} + NM_{2\gamma_2}$ and $MC_{1\gamma_1} + MC_{2\gamma_2}$, respectively. At this point, it means $\left(NM_{1\gamma_1} + NM_{2\gamma_2},\ MC_{1\gamma_1} + MC_{2\gamma_2}\right)$ is the linear amalgamation of $\left(NM_{1\gamma_1},\ NM_{2\gamma_2}\right)$ and$\left(MC_{1\gamma_1},\ MC_{2\gamma_2}\right)$. This implies an increase in the number of maintenance activities but still within the allowable threshold of maintenance activities.

Assuming that $\delta_3 = 1(\delta_1, \delta_2 = 0)$, therefore; $\gamma_0 \leq 0 : \gamma_1 \leq 0 : \gamma_2 \leq 1 : \gamma_3 \leq 1$ and $\gamma_2 + \gamma_3 = 1$ as illustrated in the third segment. Thus, number of maintenance activities and maintenance costs are $NM_{2\gamma_2} + NM_{3\gamma_3}$ and $MC_{2\gamma_2} + MC_{3\gamma_3}$, respectively. At this point, it means that $\left(NM_{2\gamma_2} + NM_{3\gamma_3},\ MC_{2\gamma_2} + MC_{3\gamma_3}\right)$ is the linear combination of $\left(NM_{2\gamma_2},\ NM_{3\gamma_3}\right)$ and $\left(MC_{2\gamma_2},\ MC_{3\gamma_3}\right)$. Therefore, the number of maintenance activities exceeds the projected threshold, leading to a corresponding significant increase in maintenance cost.

- ***Total Energy Consumption***

$$TE = \sum_{c=1}^{n} \frac{UE_c UC_e NE_{ip}}{1000} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ equation\ 6.57$$

Where TE is the total direct cost of energy consumption; UC_e is the unitary cost of energy (zar/kWh); UE_c is the unit energy requirement for treatment process (kWh) *p*; NE_{ip} is number of treatment process unit/activity

[Direct energy cost constraints]:

$$\sum_{i=1}^{n} ER_i + \sum_{r=1}^{g} ER_r \, q_r \geq 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation \; 6.58$$

$$\sum_{r=1}^{g} q_r = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation \; 6.59$$

Where ER_i is the energy requirement for the treatment process of the system with regards to allowable feed-water quality or feed water capacity, q_r is a special ordered sets of type 1 (SS1) set of 0/1 variables, with one variable a non-zero value. When $q_r = 1$, this shows that the energy requirement increased to the rth level, ER_r.

As shown in Figure 6.8, this study regards the energy cost associated with operation and maintenance treatment processes as a variable entity. Hence, the energy cost is characterized with a stepwise function associated with different chemical requirements.

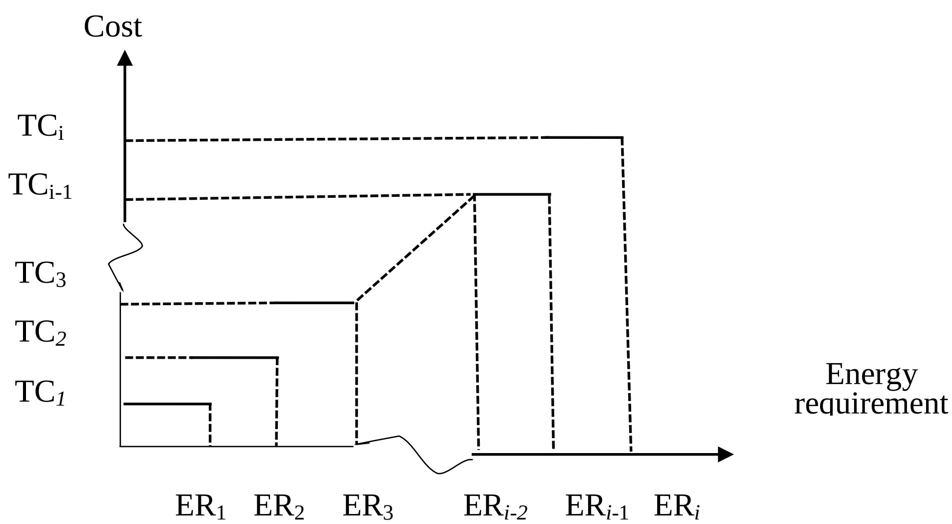


Figure 6.8: Energy cost

The overall energy cost for treatment process is TC_1 for the current feed-water quality/capacity of ER_1 energy requirement. If the water reuse system requires an increase in energy requirements $ER_2, ER_3, \ldots., ER_i$, the total energy cost will be increased to $TC_2, TC_3, \ldots., TC_i$, respectively. Equations 6.58 and 6.59 represent the constraint sets associated with the energy cost. Let ER_i represent the energy requirement for treatment process allowable for a specific feed-water quality/feed-water capacity for a water reuse system, where $(q_0, q_1, \dots., q_r)$ is a SS set of 0-1 variables with one variable being a non-zero value. The chemical quantity must be increased to *d*th quantity when $q_d = 1(d \neq 1)$, with an increase in chemical quantities doses/increase in flow-rate of feed-water.

- ***Total Residual and Waste Management***

$$SDC_t = SDC_{1\sigma_1} + SDC_{2\sigma_2} + SDC_{3\sigma_3} \dots \dots \dots \dots \dots \dots \dots \dots \; equation\ 6.60$$

$$SQ_t = SQ_{1\sigma_1} + SQ_{2\sigma_2} + SQ_{3\sigma_3} \dots \dots \dots \dots \dots \dots \dots \dots \; equation\ 6.61$$

Where SQ_t is the total sludge quantity to be disposed from water reclamation processes, $\varepsilon_0, \varepsilon_1, \varepsilon_2, \epsilon_3$ a SS1 set of 0/1 variables, with exactly one variable having a non-zero value and $\sigma_1, \sigma_2, \sigma_3$ is a SS2 set of positive variables, where two adjacent variables can have a non-zero value.

Equations 6.62-6.67 represent the constraints associated with sludge quantity and quality. SQ_t represents the quantity of sludge process from production of reclaimed water. With regards to the assumption made in this study, documenting the quality and quantity waste stream(such as sludge/biosolid) from water reclamation processes will support reuse for other beneficial purpose such as land fill usage and building construction. Furthermore, we assume that disposal costs as part of operation and maintenance cost depend to a large degree on feed-water quality, meeting the national and local guidelines for the disposal waste stream generated from treatment process, market price and local conditions. Thus, this will support lower disposal cost, support taxation policy/disposal tariff and market value of sludge/bio-solids.

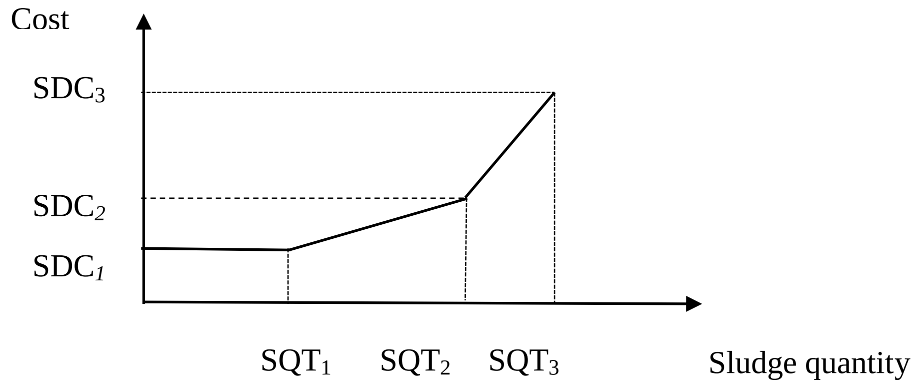


Figure 6.9: Sludge disposal cost

The total sludge quality and quantity functions is represented by a piecewise linear function consisting of three sections with different disposal tariffs as illustrated in Figure 6.9. In equations 6.53 - 6.58 $(\epsilon_1, \epsilon_2, \varepsilon_3)$ is a SS1 set of variables with just one variable a non-zero value, $(\sigma_1, \sigma_2, \sigma_3)$ is a SS2 set of positive variables with not more than two adjacent variables (Tsai et al. 2014).

$$\sigma_0 - \epsilon_1 \leq 0 \dots\dots\dots\dots\dots\dots\dots \; equation\ 6.62$$

$$\sigma_1 - \epsilon_1 - \epsilon_2 \leq 0 \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.63$$

$$\sigma_2 - \epsilon_2 - \epsilon_3 \leq 0 \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.64$$

$$\sigma_3 - \delta_3 \leq 0 \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.65$$

$$\sigma_0 + \sigma_1 + \sigma_2 + \sigma_3 = 1 \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.66$$

$$\epsilon_1 + \varepsilon_2 + \epsilon_3 = 1 \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.67$$

The first segment indicates that if $\epsilon_1 = 1(\epsilon_2, \epsilon_3 = 0)$, then $\sigma_0 \leq 1 \colon \sigma_1 \leq 1 \colon \sigma_2 \leq 0 \colon \sigma_3 \leq 0$ and $\sigma_0 + \sigma_1 = 1$. Thus, the quality and quantity of sludge/biosolids produced from water reclamation processes and disposal cost are $SQ_{1\sigma_1}$and $SDC_{1\sigma_1}$respectively. At this point, it means that $SQ_{1\sigma_1}, SDC_{1\sigma_1}$ is the linear amalgamation of (0,0) and (SQ_1, SDC_1) provided the water reclamation processes sludge quantity and quality does not surpass the least disposal tariff.

Assuming that $\epsilon_2 = 1(\epsilon_1, \epsilon_3 = 0)$, then $\sigma_0 \leq 0 \colon \sigma_1 \leq 1 \colon \sigma_2 \leq 0 \colon \sigma_3 \leq 0$ and $\sigma_1 + \sigma_2 = 1$ as illustrated in the second segment. Thus, the quality and quantity of sludge/bio-solids and disposal cost are $SQ_{1\sigma_1} + SQ_{2\sigma_2}$ and $SDC_{1\sigma_1} + SDC_{2\sigma_2}$, respectively. At this point, it means $\left(SQ_{1\sigma_1} + SQ_{2\sigma_2},\ SDC_{1\sigma_1} + SDC_{2\sigma_2}\right)$ is the linear amalgamation of $\left(SQ_{1\sigma_1},\ SQ_{2\sigma_2}\right)$ and$\left(SDC_{1\sigma_1},\ SDC_{2\sigma_2}\right)$.

Assuming that $\epsilon_3 = 1(\epsilon_1, \epsilon_2 = 0)$, therefore; $\sigma_0 \leq 0: \sigma_1 \leq 0: \sigma_2 \leq 1: \sigma_3 \leq 1$ and $\sigma_2 + \sigma_3 = 1$ as illustrated in the third segment. Thus, the quality and quantity of sludge/bio-solids and disposal cost are $SQ_{2\sigma_2} + SQ_{3\sigma_3}$ and $SDC_{2\sigma_2} + SDC_{3\sigma_3}$, respectively. At this point, it means that $\left(SQ_{2\sigma_2} + SQ_{3\sigma_3},\ SDC_{2\sigma_2} + SDC_{3\sigma_3}\right)$ is the linear combination of $\left(SQ_{2\sigma_2},\ SQ_{3\sigma_3}\right)$ and $\left(SDC_{2\sigma_2}, SDC_{3\sigma_3}\right)$. Therefore, if the water reclamation processes produce sludge/bio-solid quantity and quality that exceeds the required disposal standard, leads to a corresponding increase in disposal tariff.

- **Results and Discussion: application of the integrated cost model proposed**

This study aims to perform an empirical application of the integrated cost model suggested in the previous section. The information used for the analysis was supplied by two water reclamation plants in Mpumalanga province, in SA. The following operation and maintenance costs components were estimated-labor cost, energy cost, chemical cost, and cost of maintenance sessions/activities. Waste management and disposal cost was not estimated due to the lack of data. The two water reclamation plants utilize concrete embankment for storage of non-recyclable waste products at close proximity to the plants. Appendix 7 contains the data spreadsheet used the analysis. In plant A, fifteen chemicals and reagents are used for the treatment process and plant B fourteen chemicals and reagents. A full list of the chemical and reagent used for the treatment product is included in the appendix 7. The study estimates the O &M costs utilized due to the current capacities of Plant A (586.89 Ml/month) and Plant B (432.98 Ml/month). Appendix 7 shows the current chemicals/treatment reagent cost and quantities at the existing plant capacity.

For instance in plant A, the chemical requirement for treatment is 2183.04g/m^3 at cost 587.08Zar/kg, increasing the plant capacity, we assume a stepwise increase in chemical requirement from to 4366.08 g/m^3 or 6549.12g/m^3 and chemical cost from 587.08

Zar/kg to TC_2 or TC_3 respectively. The cost of chemical and treatment reagents is subjected to market conditions as well. Changes in market conditions and changes in feed water quality (i.e., an increase or decrease from the maximum allowable limits of pollutants in the feed water) will result in an increase/decrease in cost (g/m^3) of treatment chemicals and reagents. For the cost of labor estimation, we assume 2604 labor hours a month (i.e., a 12 hours shift for 31 days in a month by all the labor personnel) for plants A and B at the cost of Zar 909.47/hour and Zar 359.76/hour respectively. The cost of labor is denoted by LC_1. An increase in labor hours due to increase in plant capacity will result in increased cost of labor hours as well. The plant manager will use his/her discretion to assign working overtime or extra shifts. We assume a linear function for the current number of hours to increases from 2604 hours to 2704hours or 2904 hours and labor cost to increase from LC_1 to LC_2 or LC_3 respectively.

Capacity increase will result to increase in the number of treatment units as well. An increase in the number of treatment units leads to increase in energy requirements for reclaimed water treatment. These constraints are reflected in the constraints equation 6.68, to 6.74 for the two plants under consideration. The result discussed in this analysis is for the current plant capacity. The equations below gives the mathematical programming related to energy consumption, chemical consumption, labor and maintenance costs modeled according to the present plant capacity.

- ***Subject to- chemical and treatment reagent constraints***

Plant A:

$$2183.04Q_0 + 4366.08Q_1 + 6549.12Q_2 \geq 0, \qquad Q_0 + Q_1 + Q_2 = 0 \ldots.\ equation\ 6.68$$

Plant B:

$$2028.89Q_0 + 4057.78Q_1 + 6086.67Q_2 \geq 0, \qquad Q_0 + Q_1 + Q_2 = 0 \ldots equation\ 6.69$$

- ***Subject to-labor constraint (labor hours)***

Plant A:

$$2604u_0 + 2704u_1 + 2904u_2 \geq 0, 0u_0 - \mu_2 \leq 0, u_0 - \mu_1 - \mu_2 \leq 0, u_2 - \mu_2 \leq 0, u_1 + u_2 + u_3 = 1, \mu_1 + \mu_2 = 0 \ldots\ldots\ldots\ldots equation\ 6.70$$

Plant B:

$$2604u_0 + 2704u_1 + 2904u_2 \geq 0, 0u_0 - \mu_2 \leq 0, u_0 - \mu_1 - \mu_2 \leq 0, u_2 - \mu_2 \leq 0, u_1 + u_2 + u_3 = 1, \mu_1 + \mu_2 = 0 \ldots\ldots\ldots equation\ 6.71$$

- ***Subject to-maintenance constraint***

Plant A:

$$160\gamma_1 + 240\gamma_2 + 480\gamma_3 \geq 0, \gamma_0 - \delta_1 \leq 0, \gamma_1 - \delta_1 - \delta_2 \leq 0, \gamma_2 - \delta_2 - \delta_3 \leq 0, \gamma_3 - \delta_3 \leq 0, \gamma_0 + \gamma_1 + \gamma_2 + \gamma_3 = 1, \delta_1 + \delta_2 + \delta_3 \ldots. equation\ 6.72$$

Plant B:

$$110\gamma_1 + 165\gamma_2 + 330\gamma_3 \geq 0, \gamma_0 - \delta_1 \leq 0, \gamma_1 - \delta_1 - \delta_2 \leq 0, \gamma_2 - \delta_2 - \delta_3 \leq 0, \gamma_3 - \delta_3 \leq 0, \gamma_0 + \gamma_1 + \gamma_2 + \gamma_3 = 1, \delta_1 + \delta_2 + \delta_3 \ldots equation\ 6.67$$

- ***Subject to-energy constraint***

Plant A:

$$586.89q_0 + 880.335q_1 + 1760.67q_2 \geq 0, \qquad q_0 + q_1 + q_2 = 0 \ldots\ldots.. equation\ 6.73$$

Plant B:

$$432.93q_0 + 649.395q_1 + 1298.79q_2 \geq 0, \qquad q_0 + q_1 + q_2 = 0 \ldots. equation\ 6.74$$

Plant A: Overall O & M costs estimation model

$$587.08Q_0 + 1174.16Q_1 + 1682.24Q_2 + 2368272.5u_0 + 3552408.75u_1 + 71048175u_2 + 735938.33\gamma_1 + 1103907.495\gamma_2 + 2207814.99\gamma_3 + 4530q_0 + 6795_1 + 13590q_2 \ldots\ldots\ldots equation\ 6.75$$

Plant B: Overall O & M costs estimation model

$$402.61Q_0 + 805.22Q_1 + 1207.83Q_2 + 936822u_0 + 1405233u_1 + 2810466u_2 + 425984\gamma_1 + 638976\gamma_2 + 1277952\gamma_3 + 2180q_0 + 3270_1 + 6540q_2 \ldots\ldots equation\ 6.76$$

$$Q_0 = 1, Q_1 = 0, Q_2 = 0, u_0 = 1, u_1 = 0, u_2 = 0, \mu_1 = 0, \mu_2 = 0, \gamma_0 = 0, \gamma_1 = 0, \gamma_2 = 0, \gamma_3 = 0, \delta_1 = 1, \delta_2 = 0, \delta_3 = 0, q_0 = 1, q_1 = 0, q_2 = 0 \ldots\ldots\ldots. equation\ 6.77$$

$$OMC_T = \sum_{c=1}^{n} \frac{UC_c\,(D_c \times Q)}{Q \times 1000} + (LC_1 + (LC_2 - LC_1)u_1 + (LC_3 - LC_1)u_2) + \sum_{i=1}^{n} \frac{(NM_i \times MC_i)}{Q \times 1000} + \sum_{c=1}^{n} \frac{UE_c UC_e NE_{ip}}{1000} \ldots\ldots\ldots\ldots equation\ 6.78$$

Plant A:

$$TMC = 6.73 + \frac{(2604 \times 909.47)}{586.89 \times 1000} + \frac{(160 \times 4599.61)}{586.89 \times 1000} + \frac{4530 \times 0.9}{1000} \ldots\ldots equation\ 6.79$$

Plant B:

$$TMC = 6.39 + \frac{(2604 \times 357.76)}{432.98 \times 1000} + \frac{(110 \times 3872.58)}{432.98 \times 1000} + \frac{2180 \times 0.9}{1000} \ldots\ldots\ldots equation\ 6.80$$

- **Conclusion**

The results of equation 6.79 (Plant A) and equation 6.80 (Plant B) is shown in Table 6.12. The cost of each O&M cost component and the overall cost of O&M is shown in Table 6.12. The results show that labor cost contributes (25.09%), energy cost (25.34%), maintenance (7.76%) and chemicals and reagents costs (41.8%) to the overall

O & M costs of plant A. For plant B, labor cost contributes (18.95%), energy cost (17.19%), maintenance (8.59%) and chemicals and reagents costs (55.18%) to the overall O & M costs.

Table 6.13: Costs of operation and maintenance components

O &M components	Plant A	Plant B
Labor (zar/m^3)	4.04	2.16
Energy (zar/m^3)	4.08	1.96
Chemicals and reagents (zar/m^3)	6.73	6.29
Maintenance (zar/m^3)	1.25	0.98
Waste disposal (zar/m^3)	0	0
TMC (zar/m^3)	**16.1**	**11.4**

We considered an integrated cost analysis model for estimating O&M costs water reclamation plants for potable applications. The model shows the possibility of estimating O&M costs with regards to relevant constraints associated to production of reclaimed water. Although, we presented the results with respect to the current plant capacity, increase in plant capacity can be estimated by altering the items in the constraints equations highlighted above.

(iv) Waste (Sludge) recycling and reuse based on the nutrient and energy value of bio-solid produced from water reuse systems/schemes

Sludge characteristics vary relatively on the basis of the source of wastewater, the constituent of concern/contaminant in wastewater, wastewater treatment processes and technology, sludge treatment process and technology, end use and final disposal. Previous researches focus on the pollutant present in the bio-solids or sludge concentrate as this greatly impact the method or medium of disposal. However, sludge reuse potential based on the nutrient/energy value of bio-solid produced from water reuse systems for beneficial purposes needs to be taken into consideration. Ultimately, attention needs to paid to sludge concentrate reuse potential which has significant implications on disposal and the overall long-term impact on the sustainability of water reuse systems. Depending on the treatment unit process under consideration, equation 6.81 is used in calculating sludge reuse potential is given below:

$$SR_p = \frac{SV_r}{SV_t} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.81$$

Where,

SR_p = Sludge reuse potential

SV_t = Mixed slurry produced (Tonnes/Ml)

SV_r = Sludge reusable volume produced (Tonnes/Ml)

(v) Reliability of water reuse systems/schemes

Reclaimed/recycled water is an established and a reliable water source, especially in water-scarce areas which as well as promotes sustainable operations while reducing environmental footprint. Reuse of treated wastewater is quite independent of seasonal drought and weather variability and able to cover peaks of water demand (Alcalde Sanz and Manfred Gawlik, 2014). The approach used by previous researchers to express reliability of water reuse system is based on the percentage of time that the filtrate/effluent concentration meets the specified standard. However, in this study reliability of reclaimed/recycled supply expressed as a reflection of supply reliability of the water ruse system, i.e. the system performance to expected capacity. This is evaluated using equation 6.82 below:

$$SS_r = \frac{EC_m}{EC_m + EC_n} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.82$$

Where,

SS_r = security of supply of reclaimed water/effluent/filtrate (%)

EC_m = number of times system perform to expected capacity

EC_n = number of times system does not perform to the expected capacity

(vi) Performance of water reuse systems/schemes: Compliance with required standards for physical, chemical and microbial tests performed throughout the year (%)

Metcalf and Eddy (2004) stressed the importance of a water reclamation plant produce an effluent that meets specified permitting requirements and suitable for designated end users. The percentage of the times that the treated effluents meet/comply with the prescribed permitted requirement is a reflection of the perforce the treatment train processes. This factor is of paramount importance in water reuse sustainability because inadequate treatment can have serious health implications. On existing water reuse systems for potable applications, statistics can be used to assess the performance water reuse system based on the mean effluent/filtrate compliance measurement as shown in equation 6.83.

$$EFF_{com} = \frac{\sum_{j=1}^{N} \sum_{i=1}^{n} \frac{CC_i}{n}}{N} \times (100\%) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation \; 6.83$$

Where,

EFF_{com} = effluent/filtrate compliance index (%)

CC_i = number of test constituent of concern (i) in effluent meets required compliance standard

n = number of compliance requirement test of constituent of concern (i) in effluent

N = total number of compliance requirement test of all constituents of concern in effluent to meet required compliance standard

(vii) Water quality complaints (aesthetics)e.g., odour, colour, taste

One of the main impediments to reuse is the aesthetics factor. Visual amenity and odor are important attributes of reclaimed water that need to be given utmost attention. According to Menge (2006), the quality of the potable water blended with recycled/reclaimed water from the Windhoek water reclamation plant has been monitored over the past years using turbidity, fecal coliform, and free residual chlorine as indicators. Some water quality problems experienced with regards to augmentation of potable water with reclaimed/recycled water in the reticulation system include high turbidities and color. These emanated from the high nitrate concentrations of the recycled water from the reclamation plant, and this problem is compounded with the elevated iron and manganese concentrations and corrosiveness in borehole and surface water used for augmentation. In Namibia, seasonal taste and odor problems are experienced which can be detrimental to broader uptake of reuse and long-term sustainability. The water quality complaints (aesthetics), e.g., odor, color and taste of reclaimed water or potable water augmented with reclaimed/recycled water will be evaluated based on the water quality compliant index described by equation 6.84.

$$WC_i = \frac{NC_c + NC_O + NC_t}{TN_c} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; equation\ 6.84$$

Where,

WC_i = water quality compliant index

NC_c = recorded number of complaints about reclaimed water color

NC_o = recorded number of complaints about reclaimed water odor

NC_t = recorded number of complaints about reclaimed water taste

TN_c = total recorded number of complaints about reclaimed water

6.4.1.3 Treatment Train Qualitative Criteria

(i) Impact of water reuse system on habitat conservation/restoration

Development and implementation of alternative water management strategies such as reuse do not necessarily have to be in conflict with habitat conservation/restoration. Habitat conservation is imperative in-order to provide a balance between habitat conservation with development. For example, in the USA, their policies and habitat conservation plan to prevent and resolve controversies and conflict associated with any project aimed at urban development. To address this, a qualitative score will be assigned to determine the impact of water reuse system on habitat restoration/conservation.

(ii) Management plan for controlling disease vectors from water reuse system

In water reclamation plants, there is need for vigilant monitoring of all entities involved in conversion of wastewater into reclaimed water. This is imperative to ensure that health and safety users are not jeopardized. These components include each treatment unit, auxiliary treatment equipment, and online and real-time monitoring equipment. Most water reclamation plants for direct potable reuse are designed on the multiple barrier concept and safety measures with automatic shutdown incorporated as well in case there is deterioration in any unit treatment process. To account for the management plan put in place to control disease vectors from the deterioration of any unit treatment process, a qualitative score will be assigned.

(iii) Impact on groundwater quality

The tendency for groundwater to be polluted by water reclamation plants treatment processes is quite low. However, Soil Aquifer Treatment (SAT) is a type of treatment process that is capable of compromising groundwater quality. To account for this, a qualitative score will be assigned to each unit process as an indicator for the impact of reuse on groundwater aquifer.

(iv) Impact of water reuse system on soil quality and preservation

If not properly managed, some physical wastewater treatment processes such as constructed wetlands, oxidation ditch, and SAT can be detrimental to the soil quality limiting it's productive. The effects include sludge formation on top-soil, decrease in soil fertility and increase in soil pH. To account for this, a qualitative score will be assigned to each unit process as an indicator for the impact of water reuse system on soil quality.

(v) Operation and maintenance skill requirements

In SA, the Green Drop regulatory approach emphasizes the need for process control, maintenance and management skills for conventional wastewater treatment technologies and systems. However, water reuse projects for potable applications typically incorporate more sophisticated treatment technology and systems compared to conventional surface water and groundwater treatment. The difference in the level of skill required to operate and maintain water reuse system (especially advanced treatment unit processes) can be quite overwhelming. The level of skills required to operate, monitor, control and maintain each treatment unit process which is a reflection of the ease operation is reflected in the qualitative scores/marks assigned to them.

The weighted average technique was used to calculate the treatment train scores for each specific qualitative criterion. It is imperative that each unit process is assigned a rating for all evaluating criteria under consideration. The quantitative items (Nil, Low, Medium or High) are represented by the scores (0.1, 1, 2, and 3) respectively. The treatment train qualitative criteria are categorized as technical and environmental as shown in table 6.4. Equations 6.85-6.86 was employed to estimate the score for each qualitative criterion associated with the treatment train:

1. Calculate the average score for each criteria
2. Normalize the score relative to the type of criteria (Equations 6.85 & 6.87)
3. The overall treatment train score estimation

$$OQC_i^{tt} = \frac{\sum_{j=1}^{N} QC_{ij}^{UP}}{N} \dots\dots\dots\dots\dots\dots\dots\dots \; equation\ 6.85$$

$$QC_i^{tt} = \frac{1}{3} OQC_i^{tt} \dots\dots\dots equation\ 6.86 (dependent\ on\ the\ polarity\ of\ criterion)$$

$$NQC_i^{tt} = 1 - \frac{1}{3} OQC_i^{tt} \dots\dots \; equation\ 6.87\ (dependent\ on\ the\ polarity\ of\ criterion)$$

Where,

OQC_i^{tt} = Average score for treatment train criteria i

QC_{ij}^{up} = Individual unit process j score for criteria i

NQC_i^{tt} = Normalized treatment train score for criteria i

K = Number of individual unit processes making up the treatment train

6.5 Summary

This chapter explains the framework employed in developing the technical, economic and environmental assessment methodology of the ISI. It illustrates the building blocks of the ISI and assessment criteria based on the multi-criteria approach method. The framework provides a comprehensive structure for assessing reuse sustainability and is designed to provide stakeholders and decision-makers with a valuable tool that utilizes quantitative and qualitative criteria that permeates across technical, environmental and economic attributes of sustainability. Furthermore, this chapter presents the results of the ABEU model and the integrated cost analysis of the O&M costs of water reuse systems for potable applications. The institutional and social assessment criteria for the ISI are explained in Chapter 7.

CHAPTER 7

7 SOCIAL AND INSTITUTIONAL ASSESSMENTS OF WATER REUSE FOR POTABLE APPLICATIONS

7.1 Introduction

In an urban context, water reuse is taking a central and important role in the portfolio of water management strategies. The social and institutional challenges of water reuse are critical to achieving water reuse sustainability and alternative urban water management practices. The present challenge of the urban water sector is one of meeting public and political expectations for a reliable supply of "fit for purpose" water quality in a cost effective manner, in the face of climate change, prolonged drought events, technological innovations and increasing water demand. Government of water scarce regions across the globe are committing to water reuse initiatives as part of wider transition to total water cycle management. With increasing need for water reuse, the choice of implementation of alternative policy instruments, governance arrangements and incentives to assist promotion and coordination of water reuse initiatives also assumes increasing importance (Kandulu et al., 2010).

Relevant mechanisms and governing frameworks will have to be tasked with the provision of the rights of access, rights to exclude, rights of ownership, rights to manage source and recycle/reclaimed water in a changing world and the onuses of final application of the reuse operations. For example in SA, the need for rapid implementation and sustainability of reuse projects is made more severe with increasing frequencies of drought events which also warrant a systematic and comprehensive evaluation of alternative policy options and frameworks. These in turn require a systematic assessment of social and institutional factors. This study focuses on the alternative urban water management with focus on reuse and addresses some of the research deficits associated with the social and institutional challenges of water reuse resulting in improved understanding of these challenges which is pivotal to wider uptake of recycled/reclaimed water and acceptance. The next section provides a framework for the assessment of the social and institutional criteria used in the ISI. A schematic flow chart of the framework is shown in Figure 7.1.

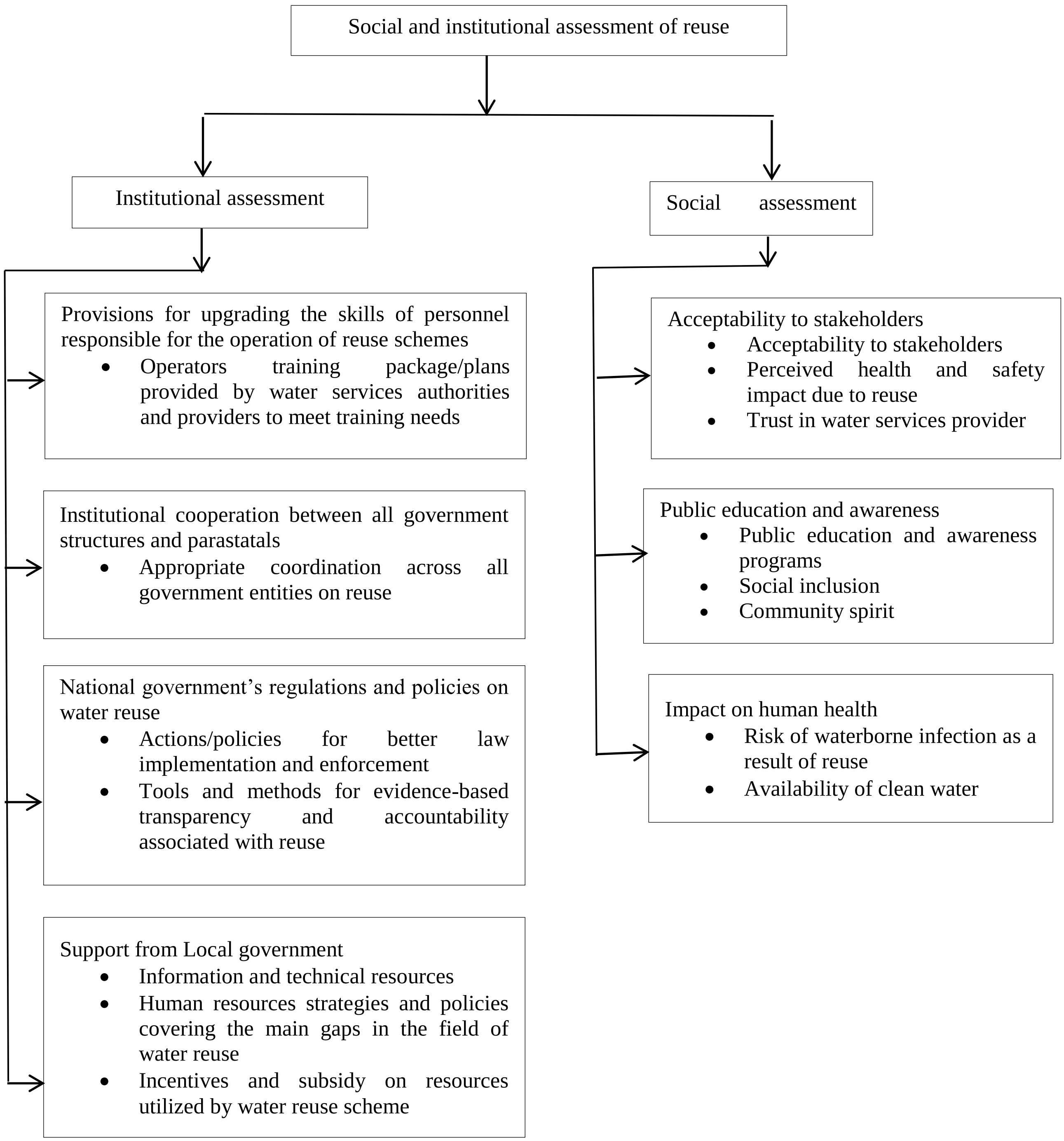


Figure 7.1: Schematic flow chart for social and institutional criteria assessment

The framework provides a robust structure for assessing water reuse sustainability for potable applications and designed to provide decision makers with criteria that cut across social and institutional attributes of sustainability. Public acceptance plays in the long term sustainability of water reuse schemes. This is evident in the implementation failures of numerous water reuse schemes (Stenekes et al., 2001; Khan and Gerrard, 2006). Past researches have indicated that there is a significant correlation between social and economic variables and levels of acceptance of reuse (Dolnicar and Sanders, 2006; Marks, 2004; Nancarrow et al., 2007).Factors widely recognized to influence public perception regard the use of reclaimed water include sources of water to be recycled, perceived health risk, degree of contact with recycled/reclaimed water, political and environmental justice issues (Jeffrey, 2002; Nancarrow et al., 2002; Kaeracher and Po, 2002; Kaercher et al., 2003; Marks et al., 2003; Hartley, 2003; Po et al.; 2004; Po et al,. 2004; Robinson et al., 2005; Friedler et al., 2006; Hurlimann and McKay, 2007; Kantanoleon et al., 2007). There are quite an ample number of perception surveys of water reuse found in literature with the majority conducted in Australia, USA, Western Europe and the Middle East. According to Friedler et al., (2006), for the purpose of developing strategies and policies for alternative water source such reclaimed water, perception studies are required in each national and sometimes sub-nation context due to variations in water availability, economy, culture and climate. According to Dobbie and Farrelly (2015), an evidence based design study to promote community acceptance towards the use of treated stormwater to mitigate water shortages was carried out by the Australian Corporate Research Centre (CRC). A significant finding from the study indicated that any empirical evidence that can inform design of community support for alternative water management strategies (e.g. use of treated stormwater) must take into consideration the local context and reflect the local context as well. Such variability makes transferability of specific findings and conclusions from one country to another somewhat problematic and irrelevant (Adewumi 2011). Furthermore,

In Durban, SA, Wison and Pfaff (2008) carried out a study to examine the fundamental religious and philosophical objections to water reuse for potable applications. The outcome of the study was compared with international experience with a conclusion that in both local and international context, generally people are not comfortable with the idea of using recycled/reclaimed water for potable applications and that fundamental religious objections to reusing recycled/reclaimed water for potable purposes does not exist in both context. Further investigation revealed that there was no empirical research on socio-psychological factors and how they influence community perceptions towards direct potable reuse in SA. This chapter primarily focuses on public perceptions towards using reclaimed water for potable applications in Mpumalanga (Emalahleni and Hendrina) and Western Cape (Beaufort West).

7.2 The Case Study Site and Survey

In order to establish a comprehensive understanding of the public perceptions with regards to water reuse sustainability within SA, three municipalities were considered namely Emalahleni, Hendrina and Beaufort West. These municipalities were identified as probable case study sites obtain necessary data for the study. Emalahleni and Hendrina municipalities are located in the Olifant WMA and Beaufort West municipality is located in the Gouritz WMA. These two WMAs are characterised with severe water shortage as indicated in Table 7.1. The estimated total water requirement in the year 2000 for Olifant and Gouritz WMAs significantly exceed the estimated total available yield in year 2000 (Table 7.1). As a form of alternative water management strategies, water reuse initiatives have being implemented in these three municipalities as measures to mitigate the severe water scarcity.

Table 7.1: Overview of the Case Study Site (adapted from Statistics South Africa, 2011)

Municipality	Emalahleni	Hendrina	Beaufort West
Province	Mpumalanga	Mpumalanga	Western Cape
Population	108673	2359	20066
Population density (persons/km^2)	662	375	381
Number of households	31308	682	5325
Average household size	3.3	2.9	3.7
Water management area	Olifant	Olifant	Breede-Gouritz
Available yield in 2000 (million m 3/annum)	609	609	275
Water requirements for the year 2000 (million m3 /annum)	967	967	337
Form of reuse	Direct potable	Direct potable	Direct potable

7.2.1 The Emalahleni, Hendrina and Beaufort West municipalities' surveys

A questionnaire was developed and randomly administered to respondent per household who are willing to participate in the study. Majority of the respondents are deemed to have a form a control over decision making process in the household. The detail of the questionnaire is available in appendix G. An introductory letter was attached to the questionnaire in order to inform the respondents of the purpose of the study and specified that any information provided would be treated with utmost confidentiality. Table 7.2illustrates the summary of respondents who participated in the study.

Table 7.2: Questionnaires administration in the three municipalities

Municipality	Emalahleni	Hendrina	Beaufort West
Number of questionnaire administered	560	255	230
Number of questionnaire returned	420	205	201

The study populations for respondent per household from the three municipalities are highlighted in Table 7.3below.

Table 7.3: Demographic information of case study sites

Demographic information	Emalahleni	Hendrina	Beaufort West
Gender			
Male	276	102	116
Female	124	103	85
Mean age range	30.45	35.65	37.46
SD (Mean age range)	7.78	6.35	7.3
Marital Status			
Single	118 (29.5 %)	90 (42.3%)	60 (30%)
Married	88 (22%)	46 (21.6%)	42 (21%)
Married with children	131 (32.8%)	65 (30.5%)	81 (40%)
Divorced	63 (15.8%)	12 (5.6%)	18 (9%)
Racial Group	Black: 302 (75%); White: 32 (8%); Asian: 22 (5.5%); Indian: 11 (2.8%); Coloured: 33 (8.3 %)	Black: 138 (64.8%); White: 37 (17.4%); Asian: 18 (8.5%); Indian: 11 (5.2%); Coloured: 9 (4.2 %)	Black: 77 (38%); White: 30 (15%); Indian: 12 (6%); Coloured: 82 (41%)

7.2.2 Questionnaire Structure

The questionnaire used for the obtaining data for the study was divided into three sections highlighted below and administered to respondents in Emalahleni, Hendrina and Beaufort West municipalities:

Section 1: The purpose of the project as well as definitions of water reuse, reclaimed/recycled water, direct and indirect potable reuse constitutes this section.

Section 2: This section provides information on water reclamation plant, water quality, and reuse for potable applications as well as problems such as perceived risk, incidence of disease outbreak etc.

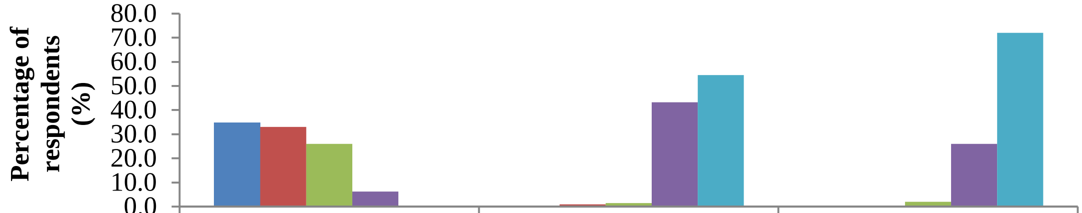
Section 3: This section identified respondents (per household) perceptions with regards to the use of reclaimed water for potable applications.

It is important to note that there were additional sections whereby certain demographic information was obtained from the respondents. These include age, gender, marital status, ethnic group and education qualification.

7.2.3 Preliminary analysis of Respondents' perceptions

- ***Aesthetic water Quality***

Aesthetics of water supply augmented with recycled water is very important to encourage reuse for potable applications among respondents. The aesthetics or yuck factor is a major reason result in rejection of reclaimed water for potable application (Adewumi et al. 2011). It is important to note that experts suggest that these reservations not be in line with reality. This is due to the fact that recycled water undergoes a process of purification that involves multiple treatment barriers which makes it often cleaner than regular drinking water (Leverenz et al. 2011). Respondents were asked to indicate the water quality of municipal water supply augmented with recycled water. Figure 7.2 indicates the respondents' perception of aesthetic water quality from the three case study sites.

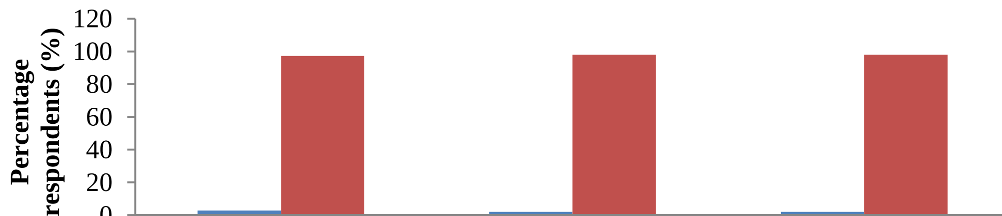


	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Unacceptable	34.8	0	0
Poor	33	0.9	0
Fair	26	1.4	2
Good	6.3	43.2	26
Excellent	0	54.5	72

Figure 7.2: Aesthetic water quality

- ***Risk of waterborne infection as a result of reuse***

In order for the public to feel safe and confident about using reclaimed water for potable application, there should be a minimal risk to health (including the risk of disease outbreak). In this study, we assume that incidence of disease outbreak is a reflection of risk of waterborne infection as a result of reuse from the water supply augmented with reclaimed water users' perspective. In Figure 7.3, over 85% of the respondent per household indicated that they are not aware of any incident of disease outbreak or report of any occurrence of disease outbreak since they have been using the municipal water supply augmented with recycled water. This can be attributed to the stringent treatment standards for reuse for potable application by the municipality. However, as shown in Figure 7.3about 3% of respondents reported cases of diarrheal and digestive disorders.

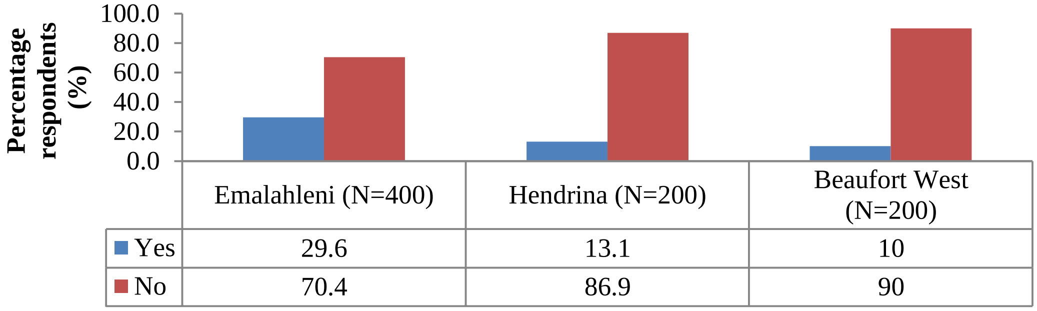


	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Yes	2.8	2	2
No	97.2	98	98

Figure 7.3: Incidence of disease outbreak

- ***Perceived health and safety impact due to reuse***

Figure 7.4illustrates respondent's perceived risk with regards to using reclaimed water for potable application. 70.4%, 89.6% and 90% of respondents in Emalahleni, Hendrina and Beaufort West municipalities respectively showed no anxiety of any risk or safety issues using reclaimed water for potable applications.

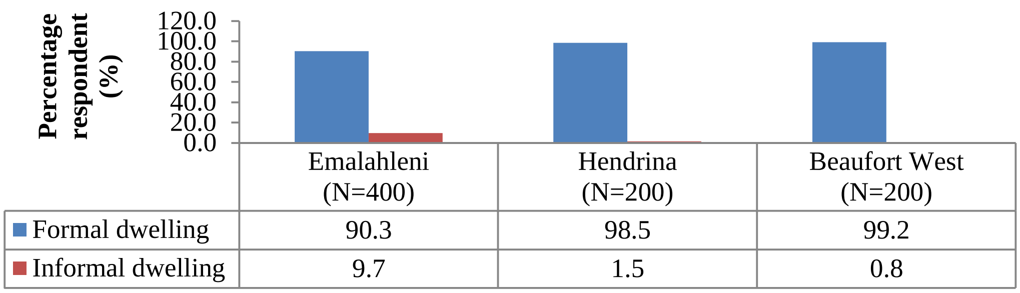


	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Yes	29.6	13.1	10
No	70.4	86.9	90

Figure 7.4: Perceived risk in the use of reclaimed water for potable applications

- ***Availability of clean water***

Over 90% of respondents per household that potable water is made available through communal pipe inside dwelling as shown in Figure 7.5. Having piped water inside dwelling contribute to availability of clean water as well as the enhance conveyance and delivery of water supply augmented with reclaimed water to the community for potable uses.

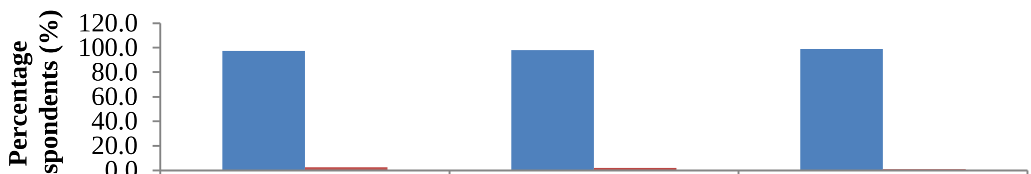


	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Formal dwelling	90.3	98.5	99.2
Informal dwelling	9.7	1.5	0.8

Figure 7.5: Piped water inside dwelling

- ***Methods of wastewater disposal***

It is imperative for areas considering reuse to have a sewerage system. In order to determine whether or not there would be adequate return flow in form wastewater from urban water consuming activities, as well as to conclude if reuse was informally occurring; respondents were requested to state how their waste-water was disposed of. Figure 7.6shows that 97.6%, 98% and 99% of respondents in Emalahleni, Hendrina and Beaufort West municipalities respectively dispose there wastewater into a sewer system.

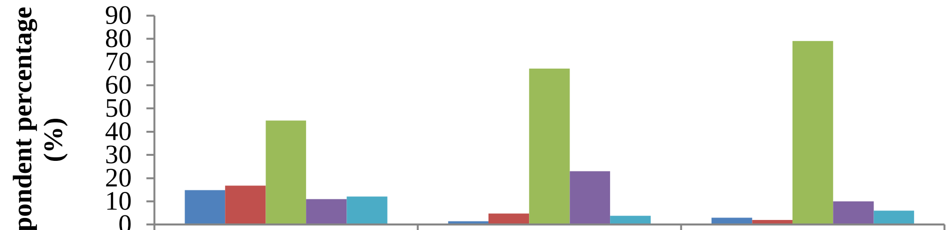


	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Sewer	97.6	98.0	99.0
Septic tank	2.4	2	1

Figure 7.6: Methods of wastewater disposal

- ***General perceptions towards reuse for potable applications***

Respondents were requested to give a description in a broad term the use of reclaimed water for potable application. An estimated 55% of Emalahleni municipality participants, 90% of Hendrina municipality participants and 79% of Beaufort West municipality participants were positive about reuse for potable applications (Figure 7.7).

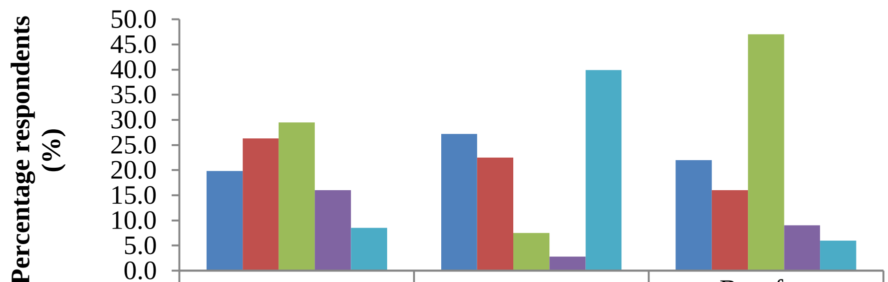


	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Disgusting	14.8	1.4	3
Unhealthy & Dangerous	16.8	4.7	2
Good & OK	44.8	67.1	79
Environmentally friendly	11	23	10
Unsure	12	3.8	6

Figure 7.7: General perceptions towards reuse for potable applications

- ***Sources of wastewater to be reclaimed for reuse***

Figure 7.8presents the result of the respondents' preferred source of wastewater to be reclaimed or "use history" of water treated for reuse for potable applications.



	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Municipal wastewater	19.8	27.2	22
On-site wastewater	26.3	22.5	16
Harvested rain	29.5	7.5	47
Storm runoff	16	2.8	9
Mine water	8.5	39.9	6

Figure 7.8: Preferred use history of water to be recycled

The results indicate specifically that the reuse of harvested rainwater and treated wastewater from one's own home was more tolerable, as opposed to water from secondary as well as public sources.

- **Public Awareness of water reuse**

Respondents were required to state whether or not they were aware of the water reclamation plant in their area which is indicative of the level of awareness that they resided in a region provided with water supply augmented with reclaimed water. Figure 7.9 shows below 21% of respondents in Emalahleni municipality, 3% of respondents in Hendrina municipality and 98% Beaufort West municipality were aware that there is a form of direct potable reuse scheme operational in their area of residence.

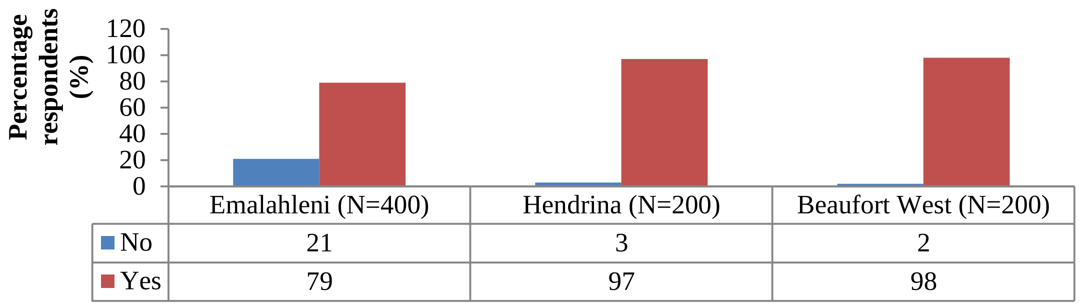


Figure 7.9: Public awareness on reuse

This brings to focus the need for water reuse sustainability through efficient public enlightenment campaigns. Without local implementation and delivery of the education program the full potential of water reuse initiatives cannot be realized. Conducting educational and awareness programs about safe and proper reuse and how imperative it is to mitigate challenges facing water supply security foster acceptability of reuse in the community. The need for such programs to cope with the increasing population mobility due to tourism and lifestyle changes emphases the importance of public education and awareness programs on reuse.

- ***Trust in water services provider***

The respondents were asked generally if they trust the governmental agency or authority responsible for provision of reclaimed water to the community will ensure that it is safe for use. Figure 7.10 shows that less than 21%, 97%, 96% of respondent per household in Emalahleni, Hendrina and Beaufort West municipalities respectively trust the municipality to ensure that the reclaimed is safe for potable applications.

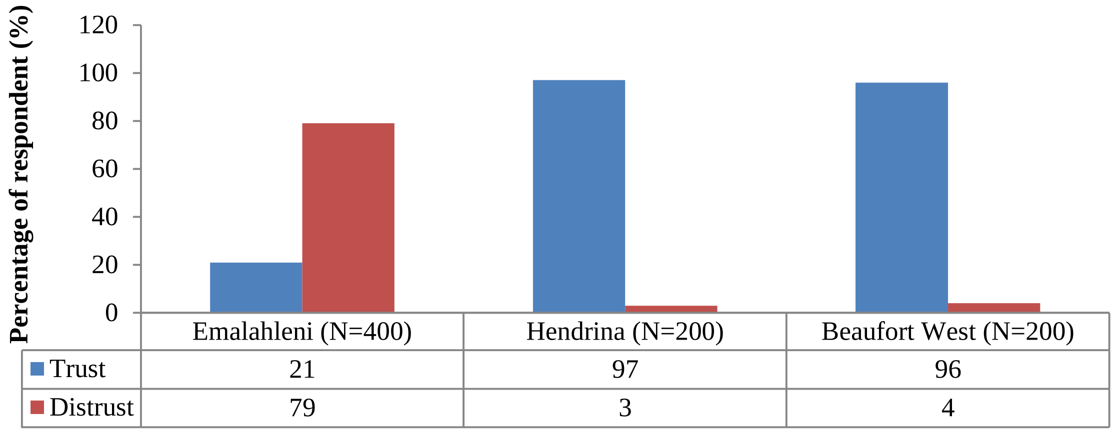


Figure 7.10: Trust in reclaimed water provider

This is indicative of trust in water service provider as well as background on the historical level of trust in water and sanitation services provider.

- ***Community spirit***

Community spirit is expressed in the willingness of community members to engage in activities that will be of benefit to the community. It is associated with voluntary work, favors and gestures of goodwill by community members as an individual or as a group. In this study, community spirit is assessed by the willingness of respondents to encourage reuse for potable applications among friends and family. Figure 7.11 shows the percentage of respondents per household willing to engage in activities to encourage reuse for potable application among friends and family as well as the community.

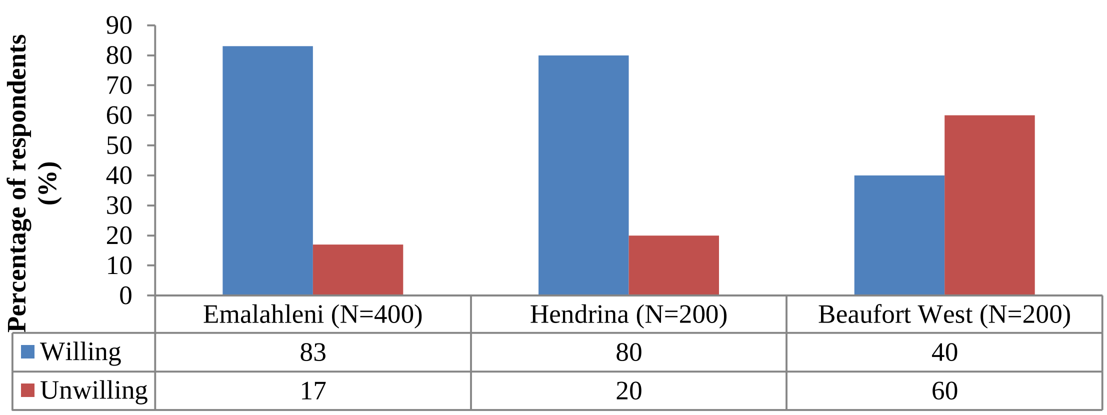
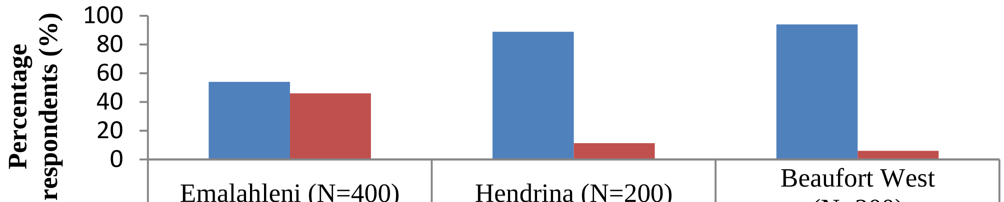


Figure 7.11: Respondents willingness to engage in activities to encourage reuse

- ***Acceptability of recycling scheme for potable applications***

Before any factor influencing intention to accept reuse for potable application was examined, respondents were asked generally about how acceptable they find water reuse for potable applications. Over 50% of the each respondent per household in the three municipalities found reuse for potable application acceptable as shown in Figure 7.12.



	Emalahleni (N=400)	Hendrina (N=200)	Beaufort West (N=200)
Acceptable	54	88.8	94
Unacceptable	46	11.2	6

Figure 7.12: Acceptability of reuse for potable applications

- ***Social inclusion***

Social inclusion is about having access to social amenities especially basic water and sanitation services (Hampson et al. 2010). In SA, formal dwellings are characterised with access to basic water and sanitation services. On the other hand, informal dwellings are characterised with poor/no access to basic water and sanitation services. This study assumed that poor/no access to basic social amenities is an indicator of poor control over natural resources and management as well as. Hence, social inclusion contributes to the efforts to sustainability in the water sector and beyond. Over 90% of the respondents in the three municipalities live in formal dwellings as shown in Figure 7.13.

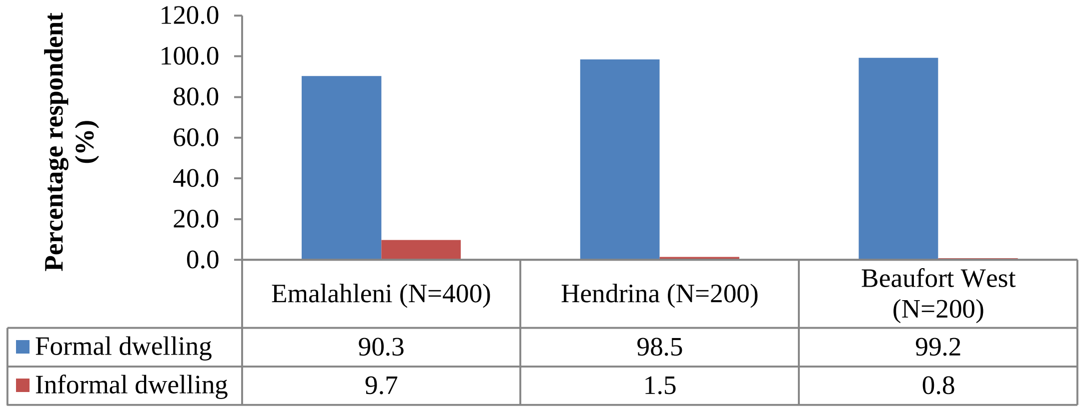


Figure 7.13: Respondents living in formal dwelling

7.3 Acceptability Reclaimed Water for Potable Uses amongst Domestic Respondents: Testing a Hypothesized Socio-Psychological Model.

7.3.1 Background

An intricate understanding of social and cultural perspective of water reuse is required for a successful implementation and sustainability of water reuse schemes (Lazarova et al., 2001). Public perceptions also play an important role on the success of water reuse schemes. Positive public perceptions towards recycled/reclaimed water use have been identified as a vital element for successful implementation and sustainability of water reuse initiatives across the globe. In America, Australia and other developed countries, some proposed water reuse scheme have failed due to lack of community support especially reuse for potable purposes (Lazarova et al 2001; Okun, 2002; Po et al., 2004, Rose et al, 2014). Acceptance of water reuse and positive public perceptions are widely recognized as key component for the successful introduction of water reuse projects (Friedler and Lahave, 2006; Nancarrow et al., 2008; Dolnicar and Hurlimann, 2011). Within the past two decades, numerous research studies have been conducted facilitate the understanding of what motivates people's behaviour as well as their decisions with regards to reuse of treated waste water for direct, indirect, potable and non-potable applications. Studies by Po, et al. (2004); Po & Nancarrow (2004); Friedler and Lahav, (2006); Nancarrow et al., (2008); Dolnicar et al., (2010, 2011); Dolnicar and Hurlimann, (2011) have presented various a few behavioural theories to predict behaviour in a variety of contexts. The most common one is the Ajzen's Theory of Planned Behaviour (Ajzen 1985)

Similar research by Syme & Nancarrow (2006) in the field of food technology and risk management offered additional understandings of predicting intended behaviour towards reuse. The results of these research studies on public preference with regards to water reuse have resulted in the development of numerous socio-psychological and religious-philosophical variables that can predict attitudes toward reuse were identified. Based on the results of study by Po et al (2005) which highlighted potential measures for observed actual behaviour towards reuse, a revised Ajzen's theory of planned behaviour model of intended behaviour was hypothesized as shown in Figure 7.14. This revised Ajzen's theory of planned behaviour model was applied to two case studies both in Australia, one involving indirect potable reuse through aquifer recharge in Perth and reuse for horticultural irrigation in Melbourne. With the exclusion of some variables from the original hypothesised model, a similar predictive model was generated from the two case study sites. (Po et al. 2005).

A number of recommendations for the revised Ajzen's theory of planned behaviour model for intended behaviour were also evident from the result of the study. Leviston et al. (2006) carried out a study which applied a modified predictive behavioural model for aquifer recharge as an indirect potable application. The model from this study duplicated the basic variables from the previous case studies. Blair et al. (2007) employed the use the modified hypothesized model by Leviston et al. (2006) to investigate the acceptability of reuse for indirect potable application in South East Queensland, Australia. The model of behavioural intention in Figure 7.15 was hypothesised for both studies, with the model variables description in Table 7.4below.

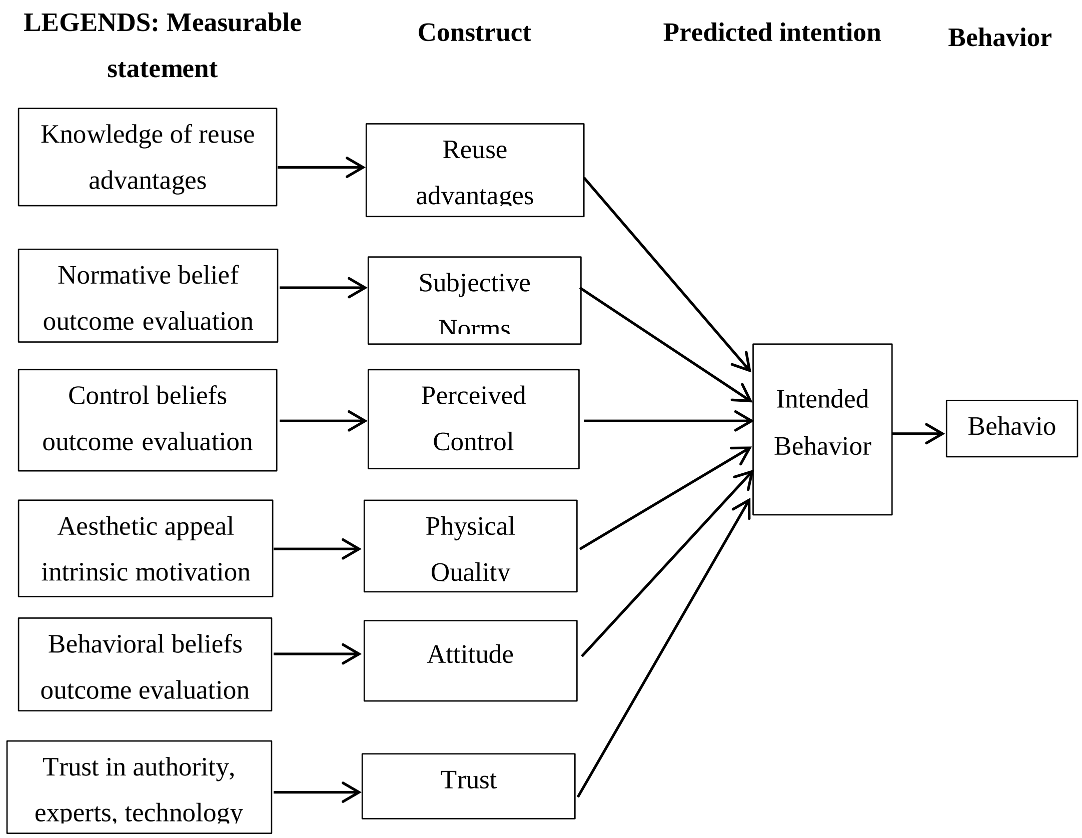


Figure 7.14: The revised Ajzen's theory of planned behaviour by Po et al., (2005)

Generally risk to health is the major public concern regarding the use of recycled/reclaimed water. In Durban, SA, Wison and Pfaff (2008) carried out a study to examine the fundamental religious and philosophical objections to water reuse for potable applications. The outcome of the study was compared with international experience with a conclusion that in both local and international context, generally people are not comfortable with the idea of using recycled/reclaimed water for potable applications and that fundamental religious objections to reusing recycled/reclaimed water for potable purposes does not exist in both context. Taking into consideration the limited studies conducted on explaining theory to determine perceptions and intended behavior with respect to reuse for potable applications, this study puts forward a hypothesized model to investigate intention to accept recycled/reclaimed water for potable applications.

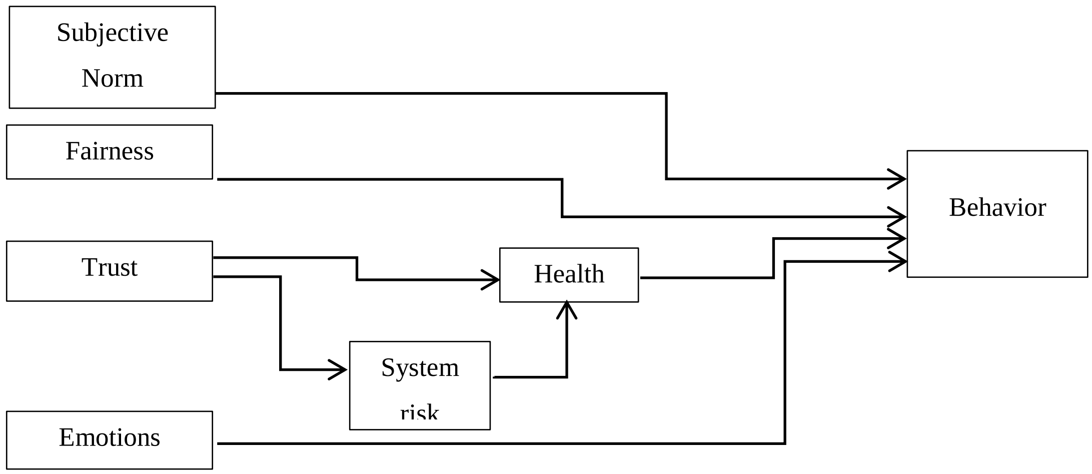


Figure 7.15: Hypothesized model of intended behavior in relation to purified recycled water (Blair et al. 2007)

Table 7.4: Descriptions of the variables in the hypothesized model (Leviston et al. (2006))

Variable	Description
Subjective norm	*The amount of pressure and influence a person feels from other important people to support the recycled water scheme*
Fairness	*The person's evaluation of whether the recycled water scheme is fair, both overall and to a variety of users*
Trust	*The extent to which a person trusts the authorities involved in implementing and managing the recycled water scheme*
Health Risk Perceptions	*The level of risk to human health a person perceives as posed by the recycled water scheme*
System Risk Perceptions	*The perceived likelihood a person has that something will go wrong with the recycled water scheme, the perceived seriousness of system failure, and how much control they perceive authorities having over system failure*
Emotion	*The extent to which a person feels negative or positive emotions towards the recycled water scheme*
Intended Behavior	*The intention to behave in a way that supports or protests against the recycled water scheme (e.g. the intention to drink the water; the intention to complain to authorities)*

7.3.2 The Hypothesized Model Development

Below we outline the theoretical and empirical basis as well as hypotheses proposed in the hypothesized model.

7.3.2.1 Knowledge of Benefits of Reuse

Knowledge of reuse advantages on the part of the public on the meaning and causes of water resources and environmental degradation and the importance of reuse as a management approach contributing to water resources preservation and environmental conservation is essential for the sustainability of water reuse projects. In this study, it is of the understanding that if the respondents are aware of the environmental issues affecting freshwater availability and good knowledge of the benefit of reuse, it will foster the intention to accept reclaimed water for drinking purposes, hence we postulate the following hypothesis:

H1: Respondents knowledge of the benefits of reuse will have a positive impact on intention to accept reclaimed water for drinking purpose

7.3.2.2 Subjective Norms (Ethical Awareness)

In this study we decide to view subjective norm from the respondent's perspectives with focus on willingness to encourage reuse among important people in the respondent's life and ethical norms towards water conservation and management. Human practices can be described as been ethically acceptable or unethically unacceptable which can result in managerial improvement or impediment to progress. Studies by Plummer and Cross (2006) and Hermann-Friede et al. (2014) illustrated the existence of ethics-related problems (such as water wastage, water pollution etc.) in the water sector and further described the detrimental impact of these problems on the sector. An individual's willingness to encourage reuse through virtuous ethical actions towards water conservation management has not been tested in acceptance of reuse for potable application. Hence the following hypothesis was articulated:

H2: Respondents willingness to engage in actions to encourage water reuse (subject norm) will have a positive impact on the intention to accept of recycled water for potable applications

7.3.2.3 The "Use History' of the Water

Studies by Jeffrey (2002); Nancarrow et al., (2002) and Kaercher et al., (2003) suggest that the source of water to be recycled, or "use history" of the water can influence acceptability of reclaimed water. Macpherson and Slovic (2011) indicated that reclaimed water is generally stigmatized by its source history ignoring its current quality and safety status. The "use history of water" to be recycled has not been investigated in the content of reuse for potable application. In this study, it is of the opinion that the respondents' indifference towards source of water to be recycled will enhance the intention to accept reuse for potable application. Hence, we propose the following hypothesis:

H3: Respondents indifference to source of wastewater to be recycled will have a positive effect on the intention to accept reclaimed water for potable applications

7.3.2.4 Predictors of Trust: Fairness, Identity, Credibility

It can be deduced from studies on procedural justice that the belief that if someone is treated fairly by relevant authorities can enhance acceptance of legal decisions, public policies evaluations and obedience to the rule of law. On the other hand, the belief that someone is treated unfairly can induce protest as a form of behavioral display (Lind, 2001; Tyler, 2001; Van den Bos and Lind, 2002). According to Syme et al., (1999); Nancarrow et al., (2002); Hurlimann et al., (2008), in the context of urban water management, it is evident that fair procedures are major predictor of acceptability of water conservation strategies and compliance with water management policies, regulations and guidelines which includes communal intentions to use reclaimed water for drinking purposes. Tyler and Lind, (1992) devised a relational model of authority which provides a theoretical explanation for findings in their study which proposes that people care more about how decisions are made than they do about the actual decisions because procedural treatment provides them with important information about their relationship with authorities (Skitka and Mullen, 2002).

A study by Tyler and Degoey (1996), suggests that the way people are treated by authorities and government agencies provides them with pertinent information about whether they are respected as been a member of a group formation, more so if they should feel a sense of pride as a member of the group as a whole. In other words, fair procedures indicate to the community members whether and how they share an identity with authorities (Ross et al., 2014). According to studies by Tyler and Degoey (1996) and Williams, (2001) shared social identity in turn produces an increase in the possibility of the group members trust in authority and accept the decisions made by the authority. Therefore, according to the relational model of authority, shared social identity is a vital mechanism by which fair procedures influence trust in authorities (Ross et al., 2014). However, this study investigates the direct relationships between shared identity and trust in WSA as well as fair procedures and trust between the relevant water authorities and the members of the community. This study examines shared identity as a reflection of the extent to which the public see the water authority as a member of their group (i.e. the community) and whether the community members perceive a sense of shared values with authority, both of which are both key dimensions of social identity (Tajfel and Turner, 1986; Tyler and Degoey, 1996; Hogg and Abrams, 1998). Studies by Siegrist et al., (2000), (2003) and Vaske et al., (2007) conceptualized value similarity as a reflection of social bonds which is consistent with this study's reasoning that it is significantly related to trust.

Tajfel and Turner (1986); Hogg and Abrams, (1998) suggest that this relational concept of trust accords with social identity theory which postulates that social groups provide members with a social identity: definition of who one is and evaluation of what that entails. Studies on social identity concept indicate that people who are members of our groups (i.e. in group membership) are perceived in a more desirable ways than out-group members (i.e. people who do not belong to our group) and that shared social identity minimizes uncertainty and results in in-group trust (Hogg and Abrams, 1998; Hogg, 2003; Brewer, 2007).

Drawing on the social identity theory, this study reasons the positive relationship between trust and shared social identity (group membership and shared identity) will enhance the acceptability of water reuse scheme. Frewer et al., (1996); Tyler and Degoey, (1996); Siegrist et al., (2003) describe source credibility as the extent to which the relevant water authority and service provider is perceived be competent and has the public's interest at heart rather than their vested interest. Previous studies have shown that when sources are perceived to be competent and credible they are trusted more (Frewer et al., 1996; Tyler and Degoey, 1996; Sutherland et al., 2013). Taking into consideration the highly technical and scientific nature of water reclamation/recycling processes, and the potential health implications on the public if the processes were to go wrong, this variable seem likely to be a key predictor of trust. The analysis performed by this study considers source credibility as an independent variable that will influence perceived judgment on trust in WSA. Studies by Williams, (2001); Tanis and Postmes, (2005); and Hogg, (2007) present ample compelling evidence that associates shared social identity to more positive evaluations of in-group members across a spectrum of group relevant dimensions. This study postulates that social identity would also influence the public's perceived judgment of trust. This study reasons that the more that people in a community, the more people will trust the WSA and service provider as well as an entity that has the vested interest of the group at heart.

H4: Respondents positive perception of procedural fairness on the part of the WSA will have a positive effect on trust in the WSA

H5: Respondents who perceive that they share the same values with the WSA will have a positive impact on trust in the WSA

H6: Respondents who believe the WSA to be a member the community they serve will have a positive impact on trust in the WSA

H7: Respondents positive perception of the credibility of water service authority (WSA) will have a positive effect on trust in WSA

7.3.2.5 Environmental Justice

(Po et. al. 2003) suggested that environmental justice issues are major factors that can impact public perception towards acceptability of water reuse initiatives. The city of San Diego came up with a reclamation project in the late 1990's which was met with strong opposition by the community. Herman Collins, a prominent local politician stated that his opposition was due to the perceived injustice as the low and medium income communities were deemed to be the major recipients of the recycled/reclaimed water (Recycled Water Task Force, 2003). This information was publicized by the politician which resulted in strong resentment from the community towards the project and invariably its demise. However, this study investigates the role that environmental justice plays in influencing trust in water service authority.

H8: Respondents perception of lack of environmental justice on the part of the WSA in water service delivery will have negative effect on trust in the WSA

7.3.2.6 Public awareness and intention to accept reuse for direct potable applications

For water reclamation for direct potable application to be generally accepted, there is the need to first dispel negative perceptions and breakdown psychological barriers with regards to reuse. With persistent and effective communication avenues as well as good marketing it can be presumed that these perceptions can be changed. Therefore, this study investigates the effect of public awareness programs on intention to accept reuse for direct potable application.

H9: Respondents positive perception towards the public awareness programs on reuse will have a positive influence on intention to accept reuse for potable applications.

7.3.2.7 Risk Perceptions, Trust, Acceptance

In the failed water reuse project cases discussed earlier, the public was basically concerned about the possible health risk associated with recycled/reclaimed water which made it unacceptable despite reassurances provided by relevant authorities and water specialists (Hurlimann and Dolnicar, 2010; Dolnicar et al., 2010; Uhlmann and Head, 2011). A clear relationship between risk perceptions and acceptance have been established in literature thereby leading to the conclusion that perceived risk to health is a critical predictor of acceptance of recycled/reclaimed water management schemes (Okun, 2002; Eiser, 2002; Siegrist et al. 2007; Mankad and Tapsuwan, 2011; Robinson et al., 2012). Earle et al., (2007), Lofstedt and Cvetkovich, (2008) both elucidate on the issue of risk as explored in different risk communication literatures which generally agree that trust in relevant authorities to manage risk is a significant factor in the perception of risk and acceptance of risk.

Fischoff, (1999); Grabner-Krauter and Kaluscha, (2003) describes trust as a complex and multi-dimensional construct, this study employs a specific operationalization drawn from previous studies (Frewer et al., 1996; Rousseau et al., 1998; Siegrist et al., 2000; Lewicki et al., 2006) stating that: *a psychological state involving the intention to accept vulnerability based on positive expectations of the intentions or behavior of the authority responsible for the water reuse scheme.* Siegrist et al., (2000) argues that many individuals lack the resources such as knowledge, interest and time to make decisions and take action relative to science and technology; basically they rely on trust in the relevant authorities or government agencies to make decisions on their behalf.

Several authors argue that in order for adaptive strategies for water resources management schemes to be successfully implemented and sustainable, the public requires a level of trust in the relevant authorities to provide them with a safe and quality water supply (Hurlimann and Mckay, 2004; Marks and Jadoroznyj, 2005). The relationship between trust, risk and acceptance have been empirically examined as shown in some studies (Siegrist, 2000; Eiser et al., 2002; Pavlou, 2003; Siegrist et al., 2007) in the context of new technologies more specifically in relation to public acceptance or water reuse scheme for potable applications (Hurlimann et al., 2008; Nancarrow et al., 2009). Therefore, these studies and theory provide a strong foundation for the hypothesis that confidence and a great level of trust in relevant water authorities and government agencies to deliver safe recycled water will be associated with lower (health and system) risk perceptions and greater acceptance of water reuse scheme. What past researches fail to examine are the underlining factors that influences trust in relevant water authorities and water service providers. This is a critical aspect that requires attention as projections indicate increase in susceptibility of water resources to drought and water authorities and service provide will have to explore alternative water sources, including recycled/reclaimed water Hurlimann et al., 2009; Doinicar Hurlimann, 2011; Rygard et al., 2011). Understanding how trust can be developed and established amongst relevant stakeholders will be essential tool to enhance the acceptance process.

H10: Respondents trust in the WSA will have a positive effect on risk perceptions concerning using reclaimed water reuse for potable applications.

H11: Respondents who are concerned about the risk implications of reuse for potable application perception will have a negative effect on intention to accept of reclaimed water for potable

In summary, these previous studies are limited in investigating underlining social factors that can enhance understanding and how trust can be developed as this contributes significantly to community's intention to accept reuse. In this study, we explore four interrelated antecedents, how they independently influence trust as well as other socio-psychological variables in an holistic approach to investigate how they contribute to the decision making process. Previous researches often draw a distinction between relational and instrumental approaches to trust, in contrast to social relational concerns and competent judgment as a basis for trust (Tyler and Degoey, 1996; Saparito et al. 2004). However, the model in this study suggests that relational and instrumental approaches to trust may be strongly inter-related with credible judgment, procedural fairness and social relational concerns which is consistent with previous researches by Kerhof et al (2003); Edwards and Kidd (2003); Cho (2006) that argue for the compatibility of relational and instrumental approaches to understanding trust. Although, Ross et al. (2014) explored the role of trust in predicting risk perceptions and factors predicting trust but the study was limited in taking into consideration other social-psychological variables such as knowledge of reuse, environmental justice, ethical awareness and the use history of water as these variables are deem imperative to intention to accept reuse . Hence this study tests a holistic hypothesized model to investigate intention to accept recycled/reclaimed water for potable applications as shown in Figure 7.16. The hypotheses formulated for this study are highlighted in Table 7.5.

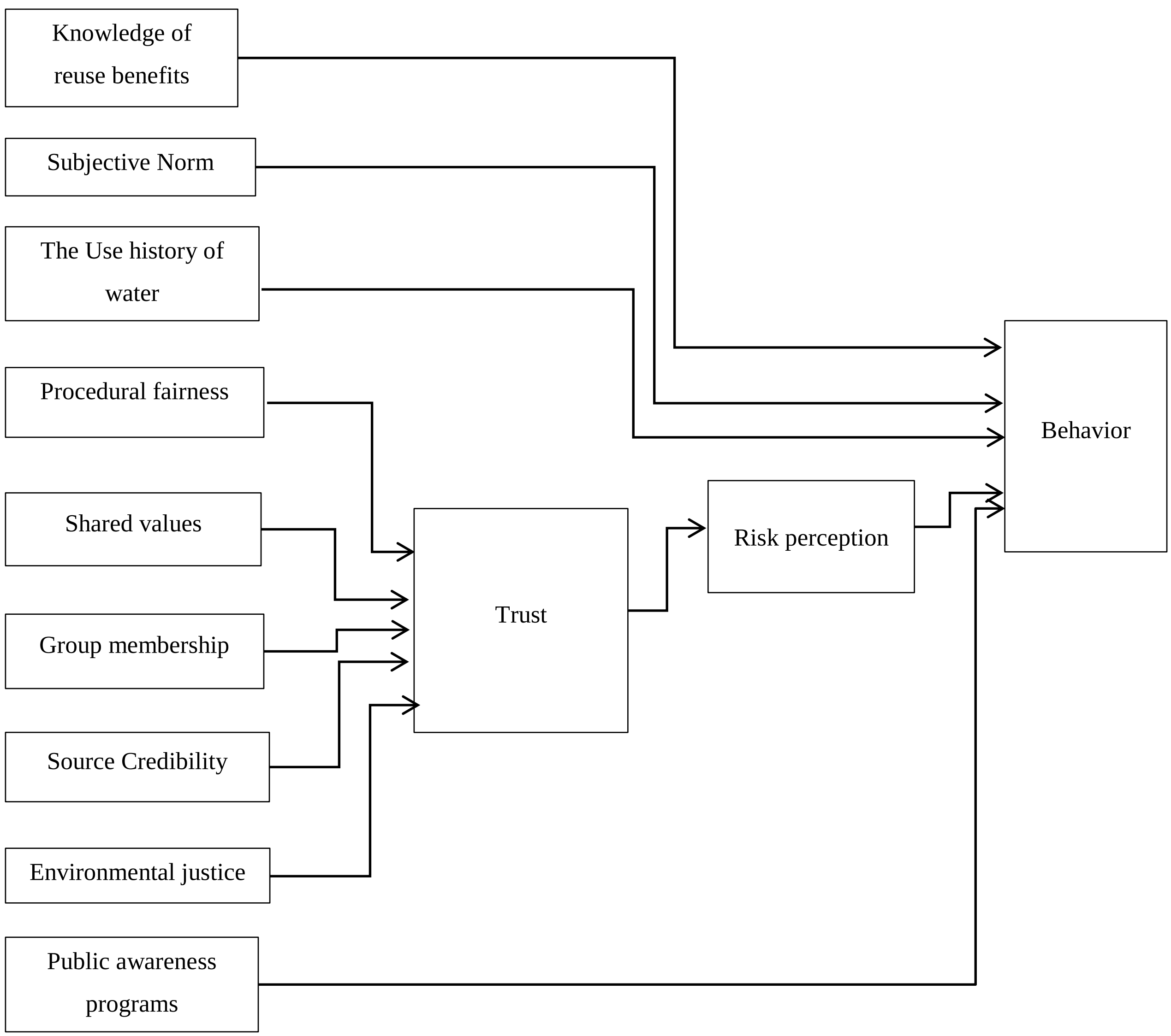


Figure 7.16: Hypothesized model for intended behavior in relation to acceptability of reuse for potable applications

Table 7.5: Intention to accept reclaimed water for potable applications hypotheses employed in the hypothesized model

Variables	Description of hypothesis
Knowledge of reuse benefits	**H1**: Respondents knowledge of the benefits of reuse will have a positive impact on intention to accept reclaimed water for drinking purpose
Subjective Norms (Ethical Awareness)	**H2**: Respondents willingness to engage in actions to encourage water reuse (subject norm) will have a positive impact on the intention to accept of recycled water for potable applications
The "Use History' of the Water	**H3**: Respondents indifference to the source of wastewater ("the use history of water") to be recycled will have a positive effect on the intention to accept reclaimed water for potable applications
Procedural fairness	**H4:** Respondents positive perception of procedural fairness on the part of the WSA will have a positive effect on trust in the WSA
Shared values	**H5**: Respondents who perceive that they share the same values with the WSA will have a positive impact on trust in WSA
Group membership	**H6**: Respondents who believe the WSA to be a member the community they serve will have a positive impact on trust in the WSA
Source Credibility	**H7**: Respondents positive perception of the credibility of water service authority (WSA) will have a positive effect on trust in the WSA
Environmental justice	**H8:** Respondents perception of lack of environmental justice on the part of the WSA in water service delivery will have negative effect on trust in the WSA
Public awareness	**H9**: Respondents positive perception towards the public awareness programs on reuse will have a positive influence on intention to accept reuse for potable applications
Trust	**H10**: Respondents trust in the WSA will have a positive effect on risk perceptions concerning using reclaimed water reuse for potable applications
Health risk perception	**H11**: Respondents who are concerned about the risk implications of reuse for potable application perception will have a negative effect on intention to accept of reclaimed water for potable applications

7.3.3 Application of the Hypothesized model to Determine Intention to Accept Reuse for Potable Applications

The purposive sampling technique (which is a non –probabilistic sampling approach) was employed for the random selection of participants in this study. Some criteria that the participants must meet include (i) respondents must be the decision makers in their respective households and (ii) must be able to understand the aim of the study. Furthermore, the sampling approach allowed for snowballing sampling technique (i.e. identifying respondent who meets the criteria for inclusion in to participate in the study) to further add more individuals to participate in the study. Participants were initially asked if they were connected to main municipal water supply (and would therefore be affected by the potable reuse scheme). Administration of questionnaires and interviews did not proceed for those not connected to the main municipal water supply. The questionnaire was designed to provide participants with explanation on water reuse scheme which included information that the wastewater would be treated to drinking water standards and then added the municipal water supply. The statements comprising the procedural fairness, perceived group membership and shared values scales were adapted from studies by Tyler and Degoey (1996); Frewer et al. (1996); Metay (1999); Siegrist et al. (2000); Poortinga and Pidgeon (2003), and (Ross et al., 2014). The source credibility scale was designed to evaluate the technical competence of the water service authority and if the water service authority has the public's interest, rather than their vested interest at heart as well (Frewer et al., 1996; Lewis and Weigert, 1985; and Ross et al., 2014). The statements for procedural fairness, shared values and source credibility were adapted from Poortinga and Pidgeon (2003); and Ross et al., (2014). The trust scale was adapted from the study by Ross et al. (2014) to capture the theoretical construct of trust as the "intention to accept vulnerability" and "positive expectations of the intentions of the other party" suggested by Rousseau et al. (1998). The statements that comprises of the risk perception scale were adapted from Hsee and Weber (1997); Weinstein (1999) and Ross et al., (2014). Intention to accept reuse for potable application was developed in terms of willingness to use the reclaimed water for a variety of uses ranging from outdoor uses to increasingly personal uses (McKay and Hurlimann, 2004; Ross et al., 2014).

According to Dawes (2008), performing statistical analysis such as regression analysis the 5-, 7- or 10- point scale formats can be used for obtaining useful data and information because the skewness and kurtosis of these three format are similar. However, the result also indicated that the 10- point scale may produce a slightly lower mean score relative to the highest possible attainable score when compared to those produced from the 5- or 7- point scale. This study employed the use of the 5-point scale as this provided a simplified list of scale descriptors for respondents to in order to avoid unnecessary and lengthy clarification associated with higher point scales since the 5-point scale have proven to produce the same result with higher scales when assessing structural equation models.

The scales for the variables influencing trust were developed as theoretically distinct and independent constructs. The items/statements representing group membership, shared values and source credibility were drawn and adapted from Ross et al. (2014). Since each construct is measured by multiple statements/items, it was imperative that the different statements/items used to evaluate the same construct should demonstrate high internal consistencies and should correlate with each other. The Cronbach's alpha (α) value is generally was used as a measure to assess the extent to which multiple items/statements used to measure a construct fit together with values varying from 0 to 1.0. The generally accepted Cronbach's alpha (α) value is greater than or equal to 0.7 as this is an indication of good internal consistency between items/statements.

The hypothesized multiple relationships between the model variables were analysed using a Structural Equation Modelling (SEM) package found in AMOS 24 software. Amos 24 employs the use of the maximum likelihood (ML) method for parameter estimation. The general form of a SEM consists of a structural model and a measurement model. The analysis of the measurement model establishes the relationship between the latent variables and observed variables. The structural equation model establishes relationships between constructs and describes their effect as well as assigns unexplained and explained variance of the endogenous construct. In this study, the average variance extracted assesses the amount of variance as a result of measurement error in relation to the amount of variance captured by the constructs.

This study adopted the two-step approach recommended by Anderson and Gerbing (1998) to analyse data obtained from the questionnaires, evaluate the relationship between the hypothesized model and data obtained. The first step involves the factor analysis to evaluate the measurement component of the constructs in the hypothesized model in order to identify items/statements of the same construct with high internal consistency. The second step entails analysing the hypothesized structural model by combining the measurement and theoretical model.

7.3.4 Results from the Application of the Hypothesized Model to Emalahleni, and Hendrina Municipalities

Table 7.6: Individual statements comprising individual construct

Construct	**Statement**
Subjective Norm	I feel personally obligated to do whatever I can to save water
	I am willing to promote the use of recycled water for drinking purposes among my friends and family
	I feel personally obligated not to dispose toxic substances into household water drains and sewers
	I am willing to use water saving devices to reduce household water consumption
Trust in water services authority	I am confident that the water service authority will ensure that the recycled water is safe
	I can depend on the water service authority to provide me with good quality water supply
	I have complete trust in the water service authority to provide me with good quality water supply
Credibility of water service authority	The municipality/MWSA provides the public with all that is to know about the water supplied to their community
	The municipality/MW SA is competent enough to manage the municipality's water supply
	The municipality/MWSA acts in the public's interest when it comes to water quality
Knowledge of benefits of reuse	The use of recycled water for drinking purposes can save many South African communities from drought and challenges facing drinking water supply.
	The use of recycled water for drinking purposes will reduce depletion of groundwater and surface water
	The use of recycled water for drinking purposes will reduce the amount of wastewater discharged to the environment
The use history	I find the source of the wastewater to be recycled for drinking purposes to very important
	I have the right to know the source of the wastewater to be recycled for drinking purposes
	I have the right to know if the water supplied for drinking purposes by the municipality is mixed with recycled water
Health Risk perception	People can get sick from using a water supply mixed with recycled water for drinking purposes on a long term basis
	I have concerns about possible problems or risks linked with the water recycling scheme for drinking purposes
Group membership	I believe the municipality/MWSA is a good representative of the people in my community
	I see the municipality/MWSA as an important member of my community
	In relation to my community, I see the municipality/MWSA as "one of us"
Procedural fairness	The municipality/MWSA makes fair decisions about water provision to all the different income class areas within the community
	The municipality/MWSA makes an effort to treat everyone within the different income class areas within the community fairly
Shared values	I believe that the municipality/MWSA has the same opinion as I do about how to provide good quality water to the municipality

	In relation to providing good quality water, the municipality/MWSA shares similar values as me
Environmental justice	I am concerned about the income class area within my community that will be the major recipient of the recycled water
	The municipality/MWSA will ensure that the recycled water is distributed to all the different income class areas within the community
Acceptability	I am willing to use recycled water for drinking purposes
	I am willing to use a recycled water for outdoor use
	I am willing to use recycled water for showering
	I am willing to use recycled water for laundry
	I am willing to use a recycled water for outdoor use
Public awareness	Adequate public education campaigns were conducted by the municipality/MWSA to provide information about the use of recycled water for drinking purpose
	The public education campaigns provides the public with everything that they need to know about the use of recycled water for drinking purposes
	The tools used by the municipality/MWSA to educate the public on the use of recycled of water for drinking purposes are effective and efficient
	The municipality/MWSA programs and information on the use of recycled water for drinking purposes is easy to get

Table 7.7: Internal consistency of statements for respondents' per household questionnaire

		Cronbach's alpha reliability	
		C1	**C2**
Construct	**Statement**		
Subjective Norm	SN1	0.77	0.78
	SN2		
	SN3		
	SN4		
Trust in water services authority	TR1	0.96	0.85
	TR2		
	TR3		
Credibility of water service authority	CR1	0.76	0.74
	CR2		
	CR3		
Knowledge of benefits of reuse	RB1	0.92	0.70
	RB2		
	RB3		
The use history	RH1	0.79	0.73
	RH2		
	RH3		
Health Risk perception	HRP1	0.86	0.83
	HRP2		
Group membership	GM1	0.96	0.70
	GM2		
	GM3		
Procedural fairness	PF1	0.82	0.73
	PF2		

Shared values	SV1	0.84	0.70
	SV2		
Environmental justice	EJ1	0.70	0.72
	EJ2		
Acceptability	WU1	0.82	0.84
	WU2		
	WU3		
	WU4		
	WU5		
Public awareness	PA1	0.98	0.78
	PA1		
	PA3		
	PA4		

Note. CS1: Emalahleni municipality; CS2: Hendrina municipality

The goodness of fits were assessed for the two sites respectively using seven practical fit indices as shown in Table 7.8.

Table 7.8: Goodness of fit for the hypothesized model

Fit index	**Recommended value (Arbuckle, 2005)**	**Emalahleni respondents**	**Hendrina respondents**
		Structural model	**Structural model**
$\frac{x^2}{df}$	≤ 5	1.134	3.315
AGFI	≥ 0.80	0.929	0.808
NFI	≥ 90	0.973	0.939
GFI	≥ 90	0.976	0.968
CFI	≥ 90	0.997	0.953
IFI	≥ 90	0.997	0.956
TLI	≥ 90	0.991	0.960
RMSEA	≤ 0.10	0.026	0.05

The average variances extracted for the statements administered to respondents in the two sites is shown in Table 7.9. The study by Rathonyi (2016) recommended a threshold value of 0.50 for variance. This was employed as the analysis of construct progressed.

Table 7.9: Average variances extracted for the respondents

Constructs	No of items	Recommended value (Rathonyi 2016)	Average variance extracted CS1	Average variance extracted CS2
Subjective Norm	4	≥ 0.50	0.716	0.751
Trust in water services authority	3		0.876	0.589
Credibility of water service authority	3		0.893	0.560
Knowledge of benefits of reuse	3		0.801	0.671
The use history	3		0.775	0.617
Health Risk perception	2		0.879	0.516
Group membership	3		0.913	0.692
Procedural fairness	2		0.705	0.577
Shared values	2		0.874	0.725
Environmental justice	2		0.735	0.617
Acceptability	5		0.735	0.604
Public awareness	4		0.796	0.751

Note. CS1: Emalahleni municipality; CS2: Hendrina municipality;

- ***Implication of the results***

Table 7.10: Path effect analysis for Emalahleni Municipality

Dependent Variable	Independent Variable	Direct Effect	Indirect Effect Through Health risk Perception	Indirect Effect Through Health risk perception and Trust	Total Effect
Behaviors	Knowledge of benefits of reuse	**0.276***	**-0.005***		0.271
	Subjective Norm	0.054	**-0.007***		0.047
	The Use history of water	0.148	**-0.011**		0.137
	Procedural fairness	0.024	0.002	**0.039***	0.024
	Health risk Perception	-0.104			-0.104
	Public awareness	-0.077	**0.005***		-0.071
	Shared value	-0.020		**0.020**	-0.020
	Group membership	0.196	0.022	**0.181**	0.026
	Environmental Justice	-0.005		**-0.090**	0.095
	Credibility	0.044		**0.002**	0.045
	Trust in water Service		**0.001***		0.001

Table 7.11: Path effect analysis for Hendrina Municipality

Dependent Variable	Independent Variable	Direct Effect	Indirect Effect Through Health risk Perception	Indirect Effect Through Health risk perception and Trust	Total Effect
Behaviors	Knowledge of benefits of reuse	**0.198***	**0.014***		0.213
	Subjective Norm	**0.164***	**0.002***		0.166
	The Use history of water	0.050	**0.004***		0.054
	Procedural fairness	**0.162***		0.039*	0.202
	Health risk Perception	**-0.111***			
	Public awareness	0.018	**-0.001***		0.013
	Shared value	0.071		0.020	0.091
	Group membership	**-.163***		0.181	
	Environmental Justice	-0.005		-0.090	-0.096
	Credibility	**0.134***		0.180	0.313
	Trust in water Service	**0.415***	**-0.008***		0.407

H1: *Respondents knowledge of the benefits of reuse will have a positive impact on intention to accept reclaimed water for drinking purpose*

The result showed that knowledge of the benefits of reuse had a positive impact on respondents' intention to accept recycled water for potable applications in Emalahleni municipality (R^2=0.276; $p<0.05$) and Hendrina municipality (R^2=0.198; $p<0.05$).

H2: *Respondents willingness to engage in actions to encourage water reuse (subject norm) will have a positive impact on the intention to accept of recycled water for potable applications*

Subjective norm had a significant positive impact on intention to accept reuse for potable application Hendrina municipality (R^2=0.164; $p<0.05$). However, the result indicates otherwise in Emalahleni municipality (R^2= 0.054; $p>0.05$).

H3: Respondents indifference to the source of wastewater ("the use history of water") to be recycled will have a positive effect on the intention to accept reclaimed water for potable applications

The result showed that the use history of water had no significant effect on the intention to accept recycled water for potable applications in Emalahleni municipality (R^2=0.148; $p<0.05$) and Hendrina municipality (R^2=0.0.050; $p<0.05$).

H4*: Respondents positive perception of procedural fairness on the part of the WSA will have a positive effect on trust in the WSA*

Procedural fairness had a significant impact on trust in WSA in Hendrina municipality (R^2=0.097; p=0.05). 9.7% of the change in variance of trust is in WSA can be attributed to procedural fairness. However, in Emalahleni municipality (R^2=0.002; $p>0.05$), procedural fairness had an insignificant impact on trust in WSA. Hence hypothesis is verified in Hendrina municipality. As shown in Table 7.11, procedural fairness has a positive significant impact on intention to accept reuse for potable application in Hendrina municipality (R^2=0.162; $p<0.05$)

In addition to H4, the direct effect of procedural fairness on intention to accept reuse was evaluated. As shown in Table 7.10, procedural fairness had a significant positive direct effect on intention to accept reuse in Emalahleni municipality (R^2=0.162; $p<0.05$). However, procedural fairness had an insignificant direct effect on intention to accept reuse for potable applications in Hendrina municipality (R^2=0.024; $p<0.05$).

H5: *Respondents who perceive that they share the same values with the WSA will have a positive impact on trust in the WSA*

Shared value has no significant direct effect on trust in the WSA in Hendrina municipality (R^2=0.015; $p>0.05$) and Emalahleni municipality (R^2=0.05; $p<0.05$)

H6: *Respondents who believe the WSA to be a member the community they serve will have a positive impact on trust in the WSA*

Group membership had a significant impact on the trust in WSA in Emalahleni municipality (R^2=0.445; $p<0.05$). This implies Emalahleni municipality, group membership contributes 44.5% of the total variance of trust in WSA. However, in Hendrina municipality, group membership had an insignificant effect on trust in the WSA (R^2=-0.022; $p>0.05$).

H7: *Respondents positive perception of the credibility of water service authority (WSA) will have a positive effect on trust in the WSA.*

In Emalahleni municipality (R^2= 0.441; $p<0.05$) and Hendrina municipality (R^2= 0.816; $p<0.05$), the credibility of WSA had a significant effect on trust in the WSA. Although in Hendrina municipality, 81.6% of total variance in trust was attributed to credibility while in Emalahleni municipality, 44.1% of the total variance in trust is linked to the credibility of the WSA.

H8: *Respondents perception of lack of environmental justice on the part of the WSA in water service delivery will have negative effect on trust in the WSA*

In Emalahleni municipality (R^2=-0.106; $p<0.05$), environmental justice had a significant effect (negative) on trust in the WSA. This implies that environmental justice contributes -10.6% of the total variance in trust in the WSA. However, in Hendrina municipality (R^2=-0.010; $p>0.05$), environmental justice had an insignificant direct effect on trust in the WSA.

H9: *Respondents positive perception towards the public awareness programs on reuse will have a positive influence on intention to accept reuse for potable application*

The results shown in Tables 7.10 & 7.11 shows that public awareness had no significant effect on intention to accept reuse for potable applications in Emalahleni municipality (R^2=0.276; $p>0.05$) and Hendrina municipality (R^2=0.018; $p>0.05$).

H10: Respondents trust in the WSA will have a positive effect on risk perceptions concerning using reclaimed water reuse for potable applications

Trust in the WSA had no direct effect on health risk perception in Hendrina municipality (R^2=0.013; $p>0.05$) and Emalahleni municipality (R^2=0.068; $p>0.05$) as shown in Tables 7.10 & 7.11.

H11: *Respondents who are concerned about the risk implications of reuse for potable application perception will have a negative effect on intention to accept of reclaimed water for potable applications*

As shown in Tables 7.10 & 7.11, health risk perception had a negative significant negative effect on intention to accept reuse for potable application in Hendrina municipality (R^2=-0.111; p<0.05). However in Emalahleni municipality (R^2=-0.104; p>0.05), health risk perception had no significant effect on intention to accept reuse for potable applications. Results of hypotheses are highlighted in Table 7.12.

Table 7.12: Results of the hypotheses that were applied to the hypothesized model

	Emalahleni		Hendrina	
Description of hypothesis	**Verified**	**Not Verified**	**Verified**	**Not Verified**
H1: Respondents knowledge of the benefits of reuse will have a positive impact on intention to accept reclaimed water for drinking purpose	*		*	
H2: Respondents willingness to engage in actions to encourage water reuse (subject norm) will have a positive impact on the intention to accept of recycled water for potable applications		*	*	
H3: Respondents indifference to the source of wastewater (“the use history of water”) to be recycled will have a positive effect on the intention to accept reclaimed water for potable applications		*		*
H4: Respondents positive perception of procedural fairness on the part of the WSA will have a positive effect on trust in the WSA		*	*	
H5: Respondents who perceive that they share the same values with the WSA will have a positive impact on trust in WSA		*		*
H6: Respondents who believe the WSA to be a member the community they serve will have a positive impact on trust in WSA	*			*
H7: Respondents positive perception of the credibility of water service authority (WSA) will have a positive effect on trust in WSA	*		*	
H8: Respondents perception of lack of environmental justice on the part of the WSA in water service delivery will have negative effect on trust in the WSA	*			*
H9: Respondents positive perception towards the public awareness programs on reuse will have a positive influence on intention to accept reuse for potable application		*		*
H10: Respondents trust in the WSA will have a positive effect on risk perceptions concerning using reclaimed water reuse for potable applications	*		*	
H11: Respondents who are concerned about the risk implications of reuse for potable application perception will have a negative effect on intention to accept of reclaimed water for potable applications		*	*	

- ***Path analysis of the hypothesized model variables on intention to accept reuse for potable applications: Emalahleni municipality***

There were significant positive relationships between the following variables: credibility of the WSA and public awareness ($r=0.383$; $p<0.05$); group membership and environmental justice ($r=0.17$; $p<0.05$); shared values and group membership; procedural fairness and environmental justice ($r=0.821$; $p<0.05$); procedural fairness and group membership ($r=0.157$;$p<0.05$); procedural fairness and shared values ($r=0.178$;$p<0.05$); the use history and group membership ($r=0.288$;$p<0.05$); the use history and shared values ($r=0.304$;$p<0.05$); subjective norm and public awareness ($r=0.182$;$p<0.05$); knowledge of reuse benefits and the use history ($r=0.732$;$p<0.05$); knowledge of reuse benefits and shared values ($r=0.339$;$p<0.05$) and knowledge of reuse benefits and group membership ($r=0.287$;$p<0.05$).

On the other hand, there was a significant negative relationship between the following independent variables: group membership and credibility ($r=-0.157$; $p<0.05$); shared values and credibility ($r=-0.126$; $p<0.05$); the use history of use and public awareness ($r=-0.169$; $p<0.05$) and knowledge of use benefits ($r=-0.182$; $p<0.05$). No significant correlation existed between shared values and credibility ($r=-0.126$; $p>0.05$). This implies that the variables in the model are suitable and appropriate.

- *Direct Effects of Independent and mediating variables (Trust in the WSA and health risk perception)on the intention to accept reuse for potable applications*

The hypothesized model revealed that there is a significant direct effect of the knowledge of reuse benefits on intention to accept reuse ($R^2=0.276$; $p<0.05$). The rest of the independent variables also had direct effect path on intention to accept reuse although there direct effects were insignificant. Public awareness ($R^2=0.276$;$p>0.05$), environmental justice ($R^2=0.095$;$p>0.05$), source credibility ($R^2=0.044$;$p>0.05$), procedural fairness ($R^2=0.024$;$p>0.05$), shared values ($R^2=-0.020$;$p>0.05$ a negative), group membership ($R^2=0.196$;$p>0.05$), the use history ($R^2=0.148$;$p>0.05$), health risk perception ($R^2=-.104$;$p>0.05$) and subjective norm ($R^2=0.054$;$p>0.05$). This implies that that directly, knowledge of use benefits is directly responsible for 27.6% of the total change in variance of the intention to accept reuse for potable applications in Emalahleni municipality

- *Direct effect of the independent variables on the mediating variables*

Further analysis of the hypothesized model revealed that the following has results that; procedural (R^2=0.002; p>0.05), shared values (R^2=0.015; p>0.05), group membership (R^2=-0.022; p>0.05) and environmental justice (R^2=-0.010; p>0.05) had no significant direct effect on trust. On the other hand, source credibility has a significant direct effect on trust (R^2=0.816; p<0.05). The magnitude of this effect is very high. The hypothesized model revealed that all the independent variables had no significant direct effect on health risk perception; knowledge of reuse benefits (R^2=0.047; p>0.05); the use history (R^2=0.104; p>0.05); subjective norms (R^2=0.064; p>0.05) and public awareness (R^2=-0.050;p>0.05 a negative insignificant effect).

- *Direct effect of mediating variables*

Trust and health risk perception are the two mediating variables. Trust precedes health risk perception in the model; hence there is a direct path. The result shows that the direct effect of trust on health risk perception is negative and insignificant (R^2=-0.013; p>0.05)

- *Indirect Effect of the Independent variables on the Mediating variables*

The indirect effects of each of the following: procedural fairness, shared values, group membership, source credibility, environmental justice and public awareness on health risk perception through trust. Only credibility has a significant indirect effect on health risk perception through trust (R^2=-.009). The remaining independent variables have no significant direct paths. This implies that credibility of the water service provider through trust is responsible for -0.9% change in behavior.

- *Indirect effect of each of knowledge of reuse benefits, subjective norm, the use history of water and public awareness through health risk perception on intention to accept reuse for potable applications*

The indirect effects of each of the three variables were found to be significant. Knowledge of reuse benefit had an indirect negative effect on intention to accept reuse for potable application through health risk perception (R^2=-005). This implies that health risk perception reduces the direct effect of knowledge of reuse benefits on intention to accept reuse by 0.5% of the total variance. This is also applicable to the indirect effects of subjective norm (R^2=-007) and the use history on intention to accept reuse (R^2=-.011).

On the other hand, the indirect effect of public awareness on intention to accept reuse through health risk perception was significant and positive; l=-005). This implies that health risk perception increases the direct effect of procedural awareness by 0.05 units on the intention to accept reuse for potable application.

- *Indirect effect of each of procedural fairness, shared values, group membership, credibility of the WSA and environmental justice through trust and health risk on intention to accept reuse for potable applications*

Only credibility had a positive significant indirect effect on behavior through trust and health risk perception respectively. This implies that the direct effect of credibility on intention to accept reuse for potable application is enhanced by trust and the perception risk to health.

- *Total effects of independent variable on intention to accept reuse for potable applications*

The knowledge of reuse benefits had the highest total effect (0.271), followed by the following: group membership (0.196), environmental justice (0.095), the use history (0.137), source credibility (0.045), public awareness (-0.071) subjective norms (0.047), procedural fairness (0.24), and shared values (-0.020).

- ***Path analysis of the hypothesized model variables on intention to accept reuse for potable applications: Hendrina municipality***

The relationship between the independent variables of the hypothesized model is discussed in this section. The following have variable no significant correlation between them: the knowledge of reuse benefits and public awareness ($p<0.05$; $r=0.140$); environmental justice and public awareness ($p>0.05$); group membership and public awareness. Procedural fairness and subjective norm correlates with public awareness. The knowledge of reuse benefits and subjective norms has no significant correlation between them. Subjective norm and the use history of water have no significant correlation. The following have significant relationship with each other: the knowledge of reuse benefits and the use history of water ($r=0.444;p<0.05$); procedural fairness and shared values ($r=0.143;p<0.05$) ; the use history of water and shared values($r=0.292;p<0.05$);the knowledge of reuse benefits and procedural fairness ($r=0.251;p<0.05$); group membership and credibility ($r=0.226;p<0.05$); shared value and credibility ($r=0.305;p<0.05$); procedural fairness and group membership ($r=0.183;p<0.05$); the use history and group membership ($r=0.290;p<0.05$); subjective norm and credibility ($r=0.240;p<0.05$); shared value and environmental justice ($r=0.143;p<0.05$); procedural fairness and environmental justice ($r=0.221;p<0.05$); the use history and environmental justice($r=0.126;p<0.05$); knowledge of reuse benefits and group membership ($r=0.293;p<0.05$); shared value and group membership ($r=0.418;p<0.05$); group membership and environmental justice; the use history and credibility; the use history and procedural fairness; knowledge of reuse benefits and shared values; credibility and environmental justice, and knowledge of reuse benefits and credibility($r=0.440;p<0.05$).

- *Direct effect of independent and mediating variables on acceptability*

Table 7.11 shows that there is a significant direct effect of: knowledge of reuse benefits ($R^2=0.198$), subjective norms ($R^2=0.164$), procedural fairness ($R^2=0.162$), health risk perception ($R^2=-0.111$), group membership ($R^2=-0.163$), credibility of the WSA ($R^2=0.134$) and trust in the WSA ($R^2=0.415$) on intention to accept reuse for potable applications This implies that the knowledge of reuse benefits contributes 19.8% of the total variance in acceptability of reuse. Furthermore, subjective norm is responsible for 16.4% of the total variance of acceptability of reuse for potable applications. Procedural fairness contributes 16.2% to the total variance of acceptability of reuse. Health risk perception negatively contributed -11.1% of the total variance in acceptability of reuse for potable applications. Group membership and credibility of the WSA were found to contribute 16.3% and 13.4% respectively to the total change in the variance of acceptability respectively. Trust in the WSA service has the highest effect, contributing a total of 41.5% to the total variance of acceptability. On the other hand, there is a direct path effect of the following: the use history of water, public awareness, shared value and environmental justice on intention to accept reuse for potable applications but there direct effects were not significant.

- *Indirect effect of the independent through health risk perception on intention to accept reuse for potable applications*

The following variables had significant indirect effect through the health risk perception on intention to accept reuse for potable applications: knowledge of use benefit (R^2=0.014), subjective norm (R^2=0.002), the use history of water (R^2=0.004), public awareness (R^2=-0.001), and trust in WSA (R^2=-0.008). This implies that the indirect effect of the knowledge of reuse benefit, subjective norm and the use history of water through health risk perception is lower than the direct effect each of the independent variables have on the acceptability of reuse for potable applications. It is important to note that the indirect effects identified were positive for the knowledge of reuse benefits (1.4%), subjective norm (0.2%) and the use history of water (0.4%).

On the other hand, public awareness (-0.1%) and trust in WSA (-0.8%) have negative indirect effects through health risk perceptions on intention to accept reuse for potable applications. This implies that health risk perception reduce the total effect of the two variables.

- *Indirect effect of the independent variable through trust and health risk perception on acceptability*

The following variables procedural fairness (R^2=0.039), shared values (R^2=0.020), group membership (R^2=0.181), credibility (R^2 =0.180) and environmental justice (-0.090) had significant indirect effect on acceptability through health risk perception.

The indirect effects through health risk perception of group membership (18.1%) and credibility (18.0%) were higher than the direct effects of each of the variables on acceptability of reuse for potable applications. This indicates the mediating effect of health risk perception and trust on acceptability increases the total effects of the two variables (credibility and group membership). It is easy to infer that the effect group membership and credibility on acceptability is better when health risk perception and trust mediates than when they are acting directly on acceptability.

The indirect effect of procedural fairness (3.9%) and shared values (2.0%) through trust and health risk perception were also positive but lower than the direct effect. On the contrary, the indirect effect of environmental justice through trust and health risk perception is negative (-9.0%) and it also have a higher magnitude than the direct effect of environmental justice on acceptability of reuse for potable applications.

- *Total effects of independent variable on intention to accept reuse for potable applications*

The result shows that the trust in the WSA had the highest total effect (40.7%) on the change in variance on intention to accept reuse for potable applications. This is followed by credibility (31.3%), knowledge of reuse benefits (21.3%), procedural fairness (20.2%), subjective norm (16.6%), environmental justice (-9.6%), shared values (9.1%), the use history of water (5.4%) and public awareness (1.3%).

7.4 Institutional Assessment of Reuse Project

Assessment of institutional capacity is a key factor in the success implementation and sustainability of water reuse projects. The outcome of an inquiry into urban water management in Australia initiated by a senate committee suggested that social and institutional challenge of water reuse is central to achieving a success and sustainable urban water management reforms. Institutional capacities and characteristics are key elements of transitioning from the business as usual approach in urban water management to exploring alternative management strategies such as reuse/recycling. Institutional factors such as organizational arrangements of water management agencies, rules and regulations governing water use and wastewater disposal management are imperative in determining whether, when, and how water reuse initiatives develop and perform. Despite the unified commitment to alternative and diversified approach to water supply, adoption and wider uptake of water reuse initiatives has yet to be realized in practice. Consultation with water experts and practitioners with knowledge on reuse in SA water sector reveals a range of systematic and institutional criteria for successful adoption and sustainability of water recycling technologies and practices which are discussed below:

(i) Operators training package/plans provided by water services authorities and providers to meet training needs

According to Muga and Mihelcic (2007), the hitch-free operation of a plant depends on the level of competence how well informed the operators are. Operator certification and training programs are used across the globe to provide a minimum standard of operational skill and knowledge for the operations of water and wastewater treatment plants. According to Walker and Stanford (2016), at the moment, there are no certification or training programs specifically designed for direct potable reuse, but instead, direct reuse utilities depend on existing water and wastewater training and certifications that plant operators are familiar. The existing water and wastewater certifications cover a plethora of essential components for potable reuse; however, there remain knowledge gaps with regards to operational know-how, treatment methodologies, and technologies as well as some of the operational tasks and methods.

In SA, the DWA recognizes the critical role of skill development for water reuse practitioners and the adequate provision of technical guidance mechanism as well as training materials to meet training needs on reuse (WRC, 2015).

(ii) Appropriate coordinating mechanism across all government entities on water reuse

The UNDP (2017) stressed the need for institutional and coordination mechanism to facilitate, integrate and cohesive implementation of sustainable development goals. Water reuse sustainability over time cannot be achieved without a certain level of integration between the different departments responsible for the various aspects of water management in an urban area. According to Frijns et al. (2016), the disintegration of responsibilities for and control over different aspects of the water cycle are barriers that must be surmounted for long-term sustainability of water reuse. Separation of powers amounts to a stalemate, inaction for an extended period, disagreement, negotiation, and complex interagency agreements that make the water reuse project far more expensive and complicated than need be (Frijns et al. 2016). Although these agencies intend to cooperate, they often have their interests to protect, and for political or economic reasons, cooperation is not achieved.

(iii) Actions toward better policies/laws for implementation and encouragement of water reuse

According to Niekerk and Schneiders, (2013), one of the biggest barriers to water reuse sustainability is a municipal, state or regional water code that does not recognize use of reclaimed water especially for potable application. The Department of Water Affairs (SA) is committed to creating a clear policy and legislative environment for sustainable water development and also a review water-related laws and regulations to assess the need for revision driven by water reuse (NWRS 2013). The onus lies on government to implement policies that will change today's approach to alternative water management strategies through policies/mandates/laws and regulation (Niekerk and Schneiders, 2013). The establishment and enforcement of a coherent government policy, publication of guidelines on water reuse, coupled with well-founded water reuse quality standards for the protection of public health and the environment is essential for the sustainability water reuse initiatives.

(iv) Tools and methods for evidence-based transparency and accountability associated with water reuse

In SA, the blue Drop and Green Drop Certification was adopted as a key regulatory program geared to recognize 'excellence' in drinking water and wastewater service quality management. Since its inception, the Blue drop score have been awarded to water reclamation plants to stimulate a holistic risk management in reclaimed water services delivery (water quality aspects). One assumption made in this research is that a blue drop award for reclaimed water service delivery serves as a tool for transparency and accountability which is important to stimulate acceptability of reclaimed water and invariably enhance the sustainability of water reuse schemes. This assumption is in-line with the OECD (2015) governance gaps (accountability gap) impeding the implementation of water related sustainable development goals.

(v) Human resources strategies and policies covering the main gaps in the field of water reuse

UNESCO initiative program on water quality highlighted human resources is one of the key capacity building elements required to ensure the quality of decision-making and managerial performance in the planning and implementation of water reclamation and reuse programs (UNEP and GEC 2002). Sustainability of water reuse requires the strengthening of local water and wastewater personnel's technical and managerial ability to evaluate limitations of current practice, potential benefits and requirements of wastewater reuse as well as the fostering of their capability to implement new programs.

(vi) ***Availability and accessibility of Information and technical resources for water reuse initiatives***

One major institutional constraint in SA regarding water project is availability and access to adequate information sources (Grobicki and Cohen, 1999; Carden, 2013). Information and responses from public institutions at local and national levels are difficult to come by due to size of relevant institutions which makes it difficult to identify individuals responsible for specific tasks. Specifically in institutions undergoing internal changes information is being lost in transit or not readily available/accessible due to physical office relocations which are also tantamount to ill-defined roles and duties of individual with the institutions. Lack of information and technical resources needed to make expert judgment can seriously impede making informed decisions necessary to support water reuse initiatives and long-term sustainability (NWRS 2011).

(vii) Incentives and subsidy on resources utilized by water reuse scheme

According to UNEP (2002); Freedman and Enssle (2015), financing opportunities and services for water reuse initiatives will need to be expanded in order to facilitate such initiatives. Incentives, such as direct subsidies, reduce government taxes for reclaimed water service provider and provision of regulatory relief for reclaimed water users through structured pricing mechanisms. For example in China, the government recognizes the effort for reuse programs by tax exemption for a period on reclaimed water production created through comprehensive resource utilization (Chang et al,2016). The establishment that provided provides and utilize reclaimed water with no economic benefits in mind is given favorable treatment through easy access to loans from banks with extended payment terms.

These qualitative criteria highlighted and described above are accounted for by using a qualitative mark will be assigned to each criterion based on the description of the mark relative to the assessment state of the criterion.

7.5 Summary

The results of this study make a vital empirical and theoretical contribution to knowledge on intention to accept reuse for potable applications by providing a broad conceptualization of knowledge of reuse benefits, the use history of water, public awareness, ethics, environmental justice, predictors of trust (shared value, procedural fairness, credibility of the WSA, group membership), risk perception and acceptability of reuse for potable applications. This research highlights the importance of direct relationship between trust and the variables such as shared value, procedural fairness, credibility and group membership. This research explores how these trust predicting variable influence trust and how trust in turn influences health risk perceptions. Invariably, we explored how risk perception influences reuse acceptability. The result shows that knowledge of reuse benefits have a significant direct effect on the intention to accept reuse. Furthermore, the result also provides vital information for planning and development of water reuse initiatives. The study highlights the significant effect of credibility of the WSA on acceptability of reuse. Credibility enhances trust in the WSA, which in turn lowers risk perception to enhance acceptability of reuse. WSA must continue to engage with the public with avenues for providing feedback on information provided to create an effective communication system. The result of this study suggests that emphasis must be placed on the benefits of reuse and efforts must be directed at presenting the WSA as a member of the community as well.

CHAPTER 8

8 CASE STUDIES OF ASSESSING THE WATER REUSE FOR POTABLE APPLICATIONS AND TESTING OF THE INTEGRATED SUSTAINABILITY INDEX AS A DECISION SUPPORT SYSTEM

8.1 Introduction

As stated in previous sections, alternative water management strategies in SA are characterized by both challenges and achievements. While progress has been made in the implementation of water reuse schemes as palliative measures to mitigate water scarcity in some communities, there are still issues with regards to acceptability, and most importantly, the long-term sustainability of these schemes. Section 7.2 describes the preliminary investigation that sets the foundation upon which assessing water reuse sustainability as part of alternative water management strategies is based. The following sections discuss the results from the water reuse sustainability assessment of the three case study sites (locations shown in Figure 1.1) and draw attention to specific challenges and areas of 'unsustainability' within these areas.

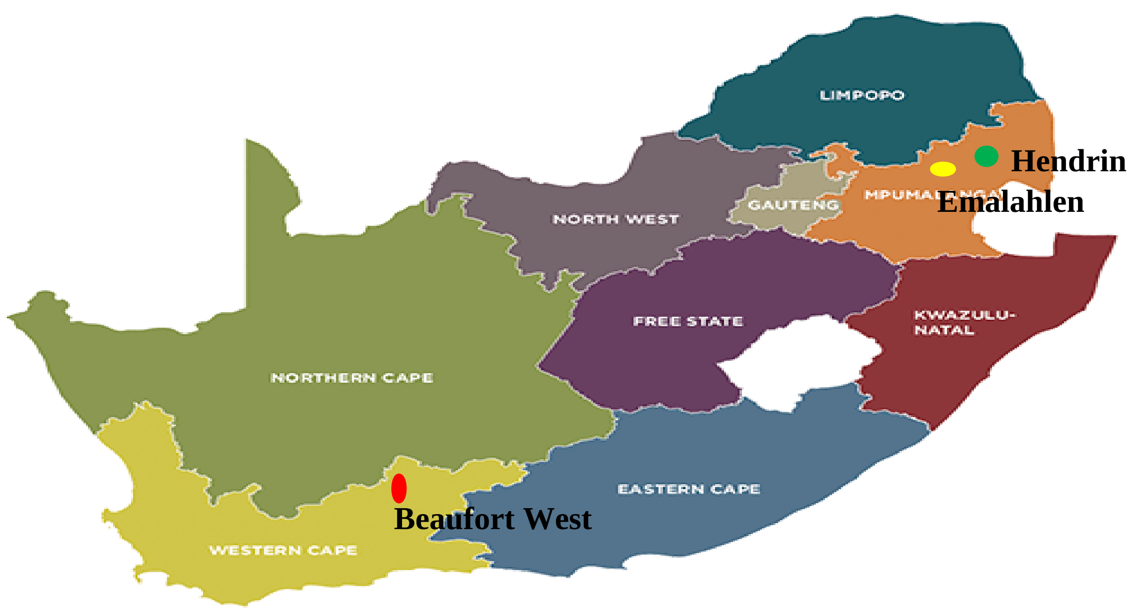


Figure 8.1: Map of South Africa showing locations of the case study sites

8.2 Decision Support System

Decision support systems (DSS) are interactive computer based systems, that help decision makers utilize data and models to solve unstructured problems. Over the last two and a half decades, major advances have been made in the development of decision support programs as a valuable tool in finding solutions to many engineering and management problems (Ndiritu and Daniel, 2001; Safaa et al., 2002; Ndiritu, 2003; Ilemobade et al., 2005; Ilemobade and Stephenson, 2006; Kahinda et al.,2009; Adewumi 2011). In the field of water reuse, this study employs software to assess the sustainability of water reuse for potable applications.

8.3 Decision Support System Structure

The name of the DSS developed in this research work is called the WRSAT is an acronym for Water Reuse Sustainability Assessment Tool. It is a software tool developed to assist stakeholders in the water sector, engineers, water resources planners, consumers and decision-makers in improving the long-term sustainability of water reuse for potable application in SA communities. International records from literature reviews indicate that water reuse initiatives till date are characterized by both failures and successes due to several factors such as environmental, technical, economic, social and institutional. WRSAT is decision support tool that consolidates all these factors in its analysis to assist decision makers to successfully assess the sustainability of water reuse schemes for potable application through identification of areas that need to be improved too for long-term sustainability of water ruse scheme as an alternative water management strategy. The Graphical User Interface (GUI) in this DSS was developed using C-SHARP. The user-friendly interface was designed as a point, drop and click to provide interactive access to input, output and action screen. The system includes the following modules and sub-modules:

1. General information: community name, province and water management area.
2. Pre-feasibility assessment: Water saving potential factor due to reuse.
3. Quantitative and qualitative (technical, economic and environment): Soil and groundwater quality preservation; security of supply, resource utilization

intensity; operation and maintenance costing information; compliance with maximum allowable water quality parameters, detailed treatment unit selection.

4. Social assessment: survey of respondents/user per household
5. Institutional assessment: indication of governance model with respect to reuse initiatives.

Each of these consists of many sub-modules which the user is guided through in sequential order to assist in decision making. A schematic flow chart of the DSS is shown in Figure 8.2. Detail description of the DSS is available in Appendix 18.

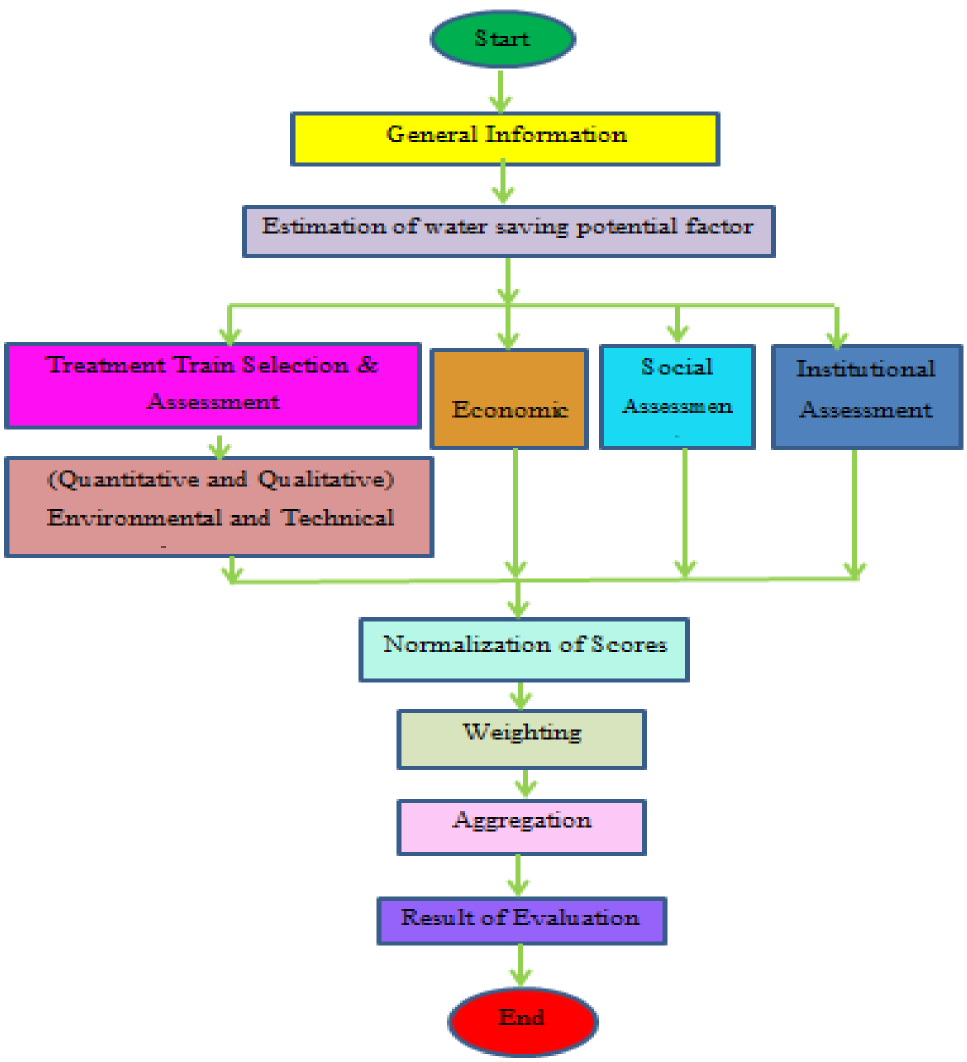


Figure 8.2: Decision support system algorithm

The ISI was applied to the three case study sites (Emalahleni, Hendrina, and Beaufort West municipalities), to assess the performance of the developed ISI in achieving the desired purpose.

8.4 Testing of the ISI (Decision Support System)

In order to examine the performance of the developed DSS in achieving the desired purpose, it was applied to three case study sites. This case study examines the environmental, economic, social technical and institutional assessment of the DSS.

8.4.1 Description of the case study sites and the water reuse schemes in operation

Figure 8.3 depicts the dialogue screen to input general information of the case study sites under consideration. Table shows the general information of the case study sites considered in this study.

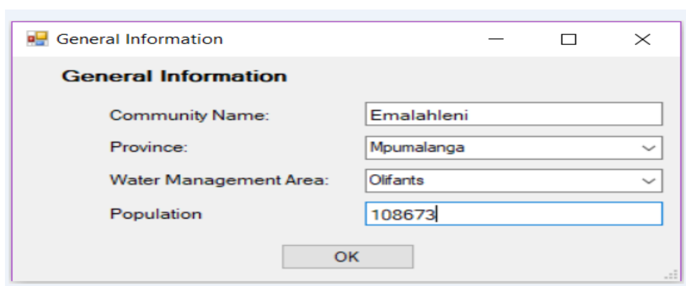


Figure 8.3: Dialogue screen for inputting general information of case study site

Table 8.1shows the general information logged into the DSS for the case study sites under consideration.

Table 8.1: General information of case study sites (source: STATSA, 2017)

Community name	Emalahleni	Hendrina	Beaufort West
Province	Mpumalanga	Mpumalanga	Western Cape
Population Water	108673	2359	20066
management area	Olifant	Olifant	Breede-Gouritz

8.4.2 Water saving potential estimation

The annual water saving potential due to reuse was estimated using the modified mass balance approach discussed in section 6.2. The modified mass balance approach was included in the ISI as a module as shown in figure 8.4 below:

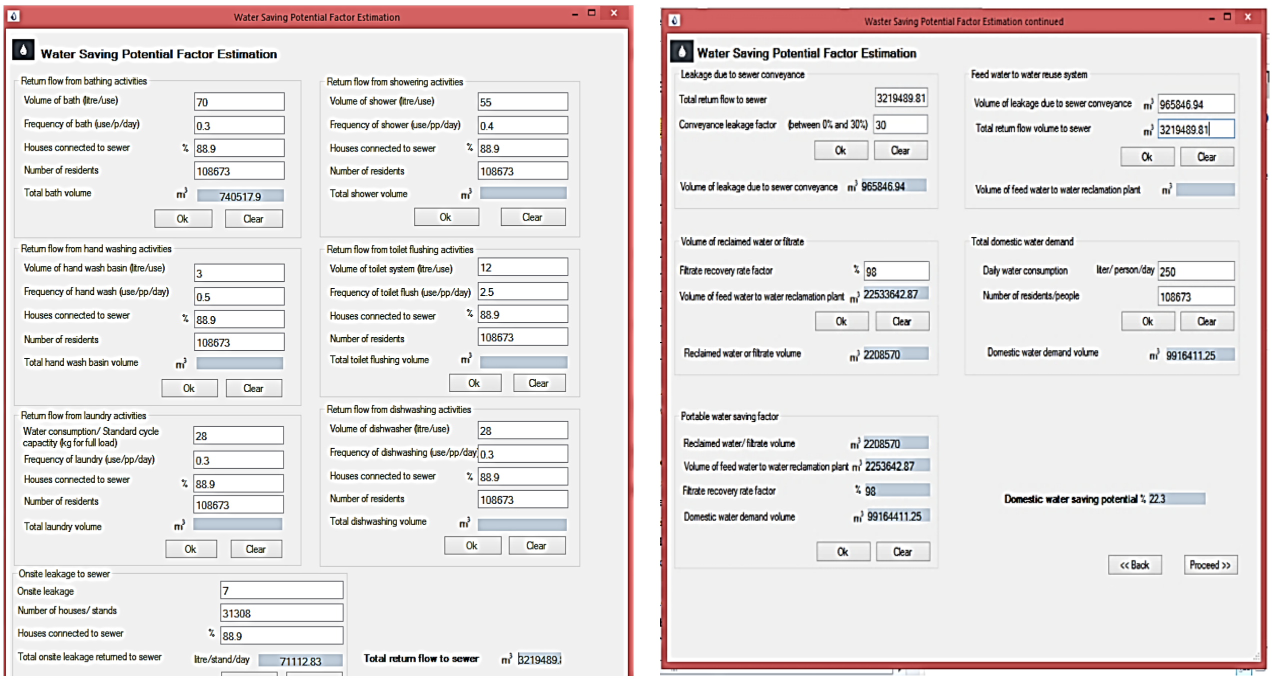


Figure 8.4: Dialog screen(s) showing water saving potential factor estimation

The data used for estimating the water saving potential excludes all the non-urban areas (sparsely populated and farming areas within Emalahleni, Hendrina and Beaufort West municipalities. The government, public and private entities have made efforts through the plethora of public awareness programs to create awareness on water management and conservation. Hence this study assumes the following figure frequency and volumes of water consumption for domestic activities as illustrated in Table 8.4. The selected frequency of activities and volume/use employed for the estimating the return flow from the six domestic activities were based on the average income class of the respective case study sites as illustrated in Tables 8.2 and 8.3.

Table 8.2: Household characteristics in the selected case study sites (Statistics SA 2011)

Municipality	Emalahleni	Hendrina	Beaufort West
Population	**108673**	**2359**	**20066**
Population density (persons/km^2)	662	375	381
Number of households	**31308**	**682**	**5325**
Average Annual household income (ZAR)	57300	15600	29400
Average income class	Middle	Low	Low
% Household connected to sewer	**88.9%**	**97.8%**	**98.9%**

Table 8.3: Definition of Income Level Used in the Study (adapted from Van Zyi et al. (2007))

Stand Value range	Income level
R20000 - R100000	Informal settlement/RDP
R100000 - R250000	**Low income/Township**
R250000 – R650000	**Middle income**
More than R650000	High income

Table 8.4 shows the domestic water demand in the South African household based on the type connection to the municipal water network and level of development. We assume that the level of development in the case study sites is an indication of the income class classification. Therefore, the domestic water demand (litre/ca/d) used for estimating the total water demand per day from Emalahleni, Hendrina and Beaufort West municipalities are 250, 80 and 130 respectively (Table8.3 & Table 8.5),. Table 8.6 shows the summary of the estimated water saving potential for the three case study sites.

Table 8.4: Frequency and volumes of water consumption for domestic activities

Parameter	High income	Middle income	Low income/Township	Informal settlement/RDP	Units
Bath frequency	0.4	**0.3**	**0.4**	0.5	Use/person/day
Bath volume	90	**70**	**40**	18	l/use
Shower frequency	0.5	**0.4**	**0.4**	0.3	Use/person/day
Shower volume	75	**55**	**45**	35	l/use
Wash hand basin frequency	0.6	**0.5**	**0**	0	Use/person/day
Wash hand basin volume	3.5	**3**	**0**	0	l/use
Toilet flush frequency	3	**2.5**	**2**	2	flushes/person/day
Toilet flush volume	12	**12**	**10**	10	l/use
Laundry frequency	0.4	**0.3**	**0**	0	washes/person/day
Laundry machine volume	28	**28**	**0**	0	l/wash
Dishwasher frequency	0.4	**0.3**	**0**	0	washes/person/day
Dishwasher volume	28	**28**	**0**	0	l/wash
Onsite leakage return to sewer	5	**7**	**8**	8	l/stand/day
On-site leakage not returned	2	**3**	**4**	4	l/stand/day

Table 8.5: Domestic water demand in developing areas equipped with full house connection (CSIR, 2003- adapted from Van Zyl et al. (2007))

Type of water supply	Typical consumption (litre/ca/day)	Range (litre/ca/d)
With full-flush and sanitation	55	60-100
House connection (developed areas)		60-475
Development level:		
Moderate	**80**	48-98
Moderate to high	**130**	80-145
High	**250**	130-280
Very high	450	260-480

Table 8.6: Water saving potential for selected case study sites

Municipality	Emalahleni	Hendrina	Beaufort West
Total water demand (m3)	9916411.25	68882.8	952131.7
Bath volume m3	740517.9	13473.5	115896.4
Shower volume m3	775780.68	15157.66	130383.45
Hand wash basin volume m3	52894.14	0	0
Toilet flushing volume	1057882.75	16841.85	144870.5
Laundry volume	296207.17	0	0
Dishwasher volume	296207.17	0	0
Onsite leakage to sewer	71112.83	1947.63	15377.96
Total wastewater generated	3290602.64	47470.64	406528.31
Conveyance Leakage factor (%)	30	30	30
Conveyance leakage loss volume	987180.79	14241.19	121958.49
Volume of feed-water to water reclamation plant	2303421.848	33229.45	284569.82
Filtrate recovery rate factor (%)	98	98	98
Volumetric flow of reclaimed water (m3)	2257353.41	32564.86	278878.42
Potable water saving factor (%)	22.8	47.3	29.3

This implies that ***potable water demand can be reduced by approximately 22.8 %, 47.3% and 29.3%*** in Emalahleni, Hendrina and Beaufort West municipalities respectively assuming the total wastewater generated was treated for potable application and no return flow of treated wastewater into receiving water bodies.

8.5 Detail Information of Unit Processes

The choice of treatment technology is mainly dependent on (i) the nature of the pollutants in the feed-water and (ii) the reclaimed water quality requirement for specific end users. Table 6.2 presented an overview of applicable treatment technologies for potable reuse in the selected case study sites. The application of multiple barriers approaches for the removal and control of pollutants from wastewater stream has proven to be one of the best practices in water reuse initiatives. This implies that the transformation of wastewater to reclaimed water involves several technological and management barriers set up to achieve a high level of assurance regarding the removal of pollutants as well as the production of reclaimed water fit for use and safe for human consumption.

In most cases, assessment of individual treatment unit processes is not considered in the monitoring process unless a specific unit process is suspected of contributing to non-compliancy with required standards. As a result, plant operators and personnel do not have data illustrating the interrelationships between the individual unit process (making up the treatment train) needed to provide optimum plant operation. In this study, the assessment of a treatment technology is based on the evaluation of each treatment unit in the treatment train. The Emalahleni and Hendrina water reclamation plants consist of the treatment configuration described by the flow process (a) and Beaufort West water reclamation plant consist of the configuration depicted by the flow process (b) as at July 2017:

a. ***Mine-water ⟶ neutralization reactors ⟶ clarifiers ⟶ ultrafiltration ⟶ reverse osmosis ⟶ chlorine contactors ⟶ purified water***
b. ***Secondary treated effluent ⟶ rapid sand filtration ⟶ ultrafiltration ⟶ reverse osmosis ⟶ advanced oxidation ⟶ chlorination/disinfection ⟶ purified water***

8.5.1 Treatment Unit Selection

The selection and implementation of the appropriate treatment technology is vital to the successful implementation and sustainability of water reuse projects. The ISI provides a platform for the selection of treatment unit to form a treatment train. Figure 8.5 shows the platform for selection of representative treatment train preliminary, secondary, advanced and disinfection treatment stages respectively.

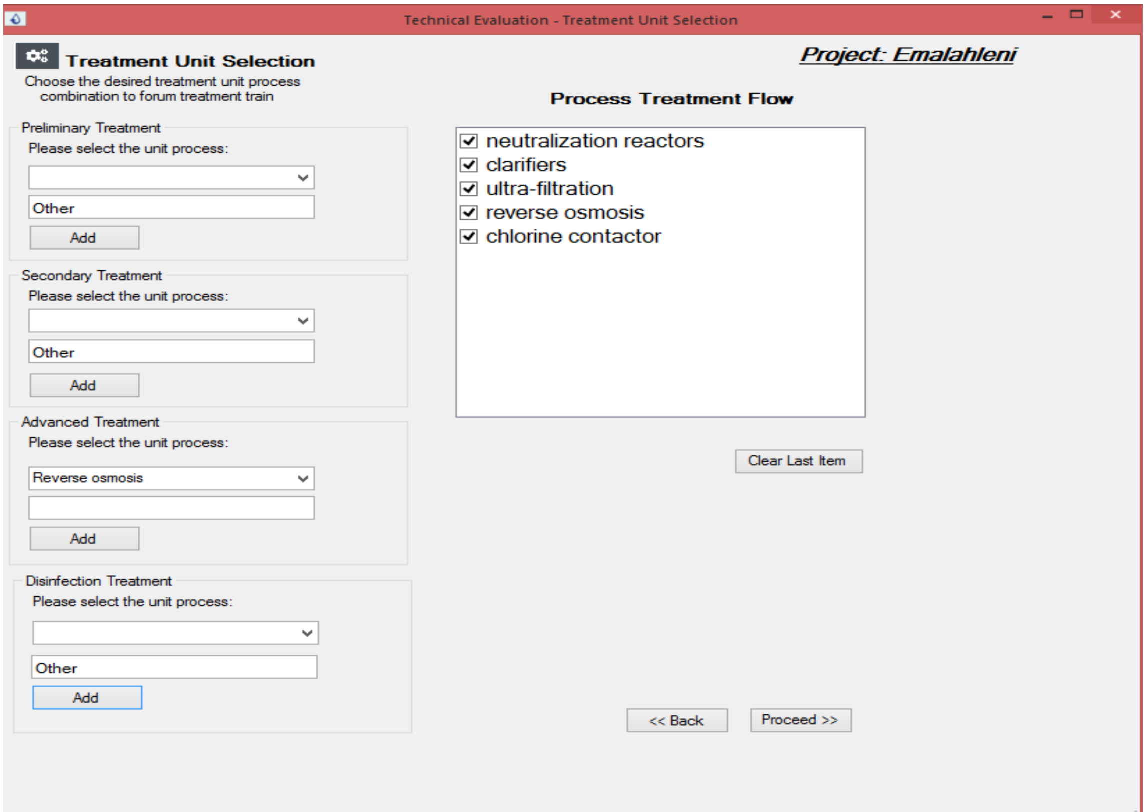


Figure 8.5: Dialogue screen for treatment train selection

8.6 Individual Sustainability Aspect

Table 8.7: Data source and polarity of evaluation criteria provides a summary of (i) the polarity of each criterion, (ii) source of information (such as surveys, results of representative model evaluation, plant operational data, interviews with experts, reclamation plant operators and municipal officers (iii) units/methods for measurement of criteria. The comprehensive details of the values for the each criterion analysis for all the case study sites is included in the Appendices 12,13, 14, 15, 16 and 17 in the compact disc labeled Appendices.

Table 8.7: Data source and polarity of evaluation criteria

Primary Criteria	Secondary Criteria	Unit/(MoM)	Polarity	Source of data
EW	EW1	Tonnes/reuse	+	RD
EI	EI1	Qualitative measure	-	LR and EK
EG	EG1	Qualitative measure	-	LR and EK
EN	EN1	Qualitative measure	-	LR and EK
	EN2	Qualitative measure	+	LR and EK
ER	ER1	KWh/m^3	-	RD
EL	EL1	ZAR/m^3	-	RD
	EL2	ZAR/m^3	-	RD
TO	TO1	Qualitative measure	-	LR and EK
TR	TR1	Number of weeks of system performed to expected capacity/annum	+	RD
TP	TP1	Compliance with required standards for physical, chemical and microbial tests performed throughout the year (%)	+	RD and EK
	TP2	Number of water quality complaints/year	-	RD
SA	SA1	%	+	RD
	SA2	%	-	RD
	SA3	%	+	RD
SP	SPI	%	+	RD
	SP2	%	+	RD
	SP3	%	+	RD
SH	SH1	%	-	RD
	SH2	%	+	RD
IP	IP1	Qualitative measure	+	EK
IC	IC1	Qualitative measure	+	EK
IN	IN1	Qualitative measure	+	EK
	IN2	%	+	RD
IS	IS1	Qualitative measure	+	EK
	IS2	Qualitative measure	+	EK
	IS3	Qualitative measure	+	EK

***EK: expert knowledge; LR: literature review; RD: real data.**

8.6.1 Evaluation Criteria Analysis

8.6.1.1 Qualitative environmental and technical criteria evaluation

A water reclamation plant (or WRS) is the physical infrastructure used for the production of reclaimed water; hence, it is central to core water reuse initiatives. Figure 8.6 depicts the dialogue screen for qualitative environmental and technical criteria evaluation: (i) spreading of toxic compound from reuse system to arable land (EI1), (ii) impact of reuse system on groundwater aquifer (EG1), (iii) impact of water reuse system on habitat/wetland restoration/conservation (EN1) (iv) management plan for controlling disease vectors from water reuse system (EN2) and (v) operation and maintenance skills requirement for water reuse system (TO1). Tables 8.8 & 8.9 provide the qualitative items assigned to each treatment train unit for assessing the qualitative criteria. The qualitative items (Nil, Low, Medium or High) represent scores (0.1, 1, 2 and 3) respectively. The qualitative item assigned to each treatment unit was based on plant information provided by plant managers (Rein, per comm, (2017); Hammond, per comm, (2017)) and literature review (Joksimovic, 2006 and Adewumi, 2011).

Table 8.8 Unit process detailed information for Emalahleni and Hendrina

Treatment unit/ process	**Qualitative environmental and technical criteria**				
	Spreading of toxic compound from reuse system to arable land	Impact of reuse system on groundwater aquifer	Impact of water reuse system on habitat/wetland restoration/conservation	Management plan for controlling disease vectors from water reuse system	Operation and maintenance skills requirement for water reuse system
Neutralization reactors	**Nil**	**Nil**	**Nil**	**Low**	**Low**
Clarifiers	**Nil**	**Nil**	**Nil**	**Low**	**Low**
Ultrafiltration	**Nil**	**Nil**	**Nil**	**High**	**Low**
Reverse Osmosis	**Nil**	**Nil**	**Nil**	**High**	**Medium**
Chlorine contractor	**Low**	**Low**	**Low**	**Low**	**Medium**

Table 8.9 Unit process detailed information for Beaufort West

Treatment unit/ process	**Qualitative environmental and technical criteria**				
	Spreading of toxic compound from reuse system to arable land	Impact of reuse system on groundwater aquifer	Impact of water reuse system on habitat/wetland restoration/conservation	Management plan for controlling disease vectors from water reuse system	Operation and maintenance skills requirement for water reuse system
Coagulation/ flocculation	**Low**	**Nil**	**Nil**	**Low**	**Low**
Sedimentation	**Low**	**Nil**	**Nil**	**Low**	**Low**
Rapid sand filtration	**Medium**	**Medium**	**Medium**	**Low**	**High**
Ultrafiltration	**Nil**	**Nil**	**Nil**	**High**	**Low**
Reverse Osmosis	**Nil**	**Nil**	**Nil**	**High**	**Medium**
Ultraviolent disinfection	**Nil**	**Nil**	**Nil**	**High**	**Medium**
Chlorine contractor	**Low**	**Low**	**Low**	**Low**	**Medium**

Figure 8.6 shows the dialogue screen for evaluating each qualitative environmental and technical assessment criteria. Figure 8.7 shows the overall qualitative assessment scores for the treatment train technology utilized in the case study sites.

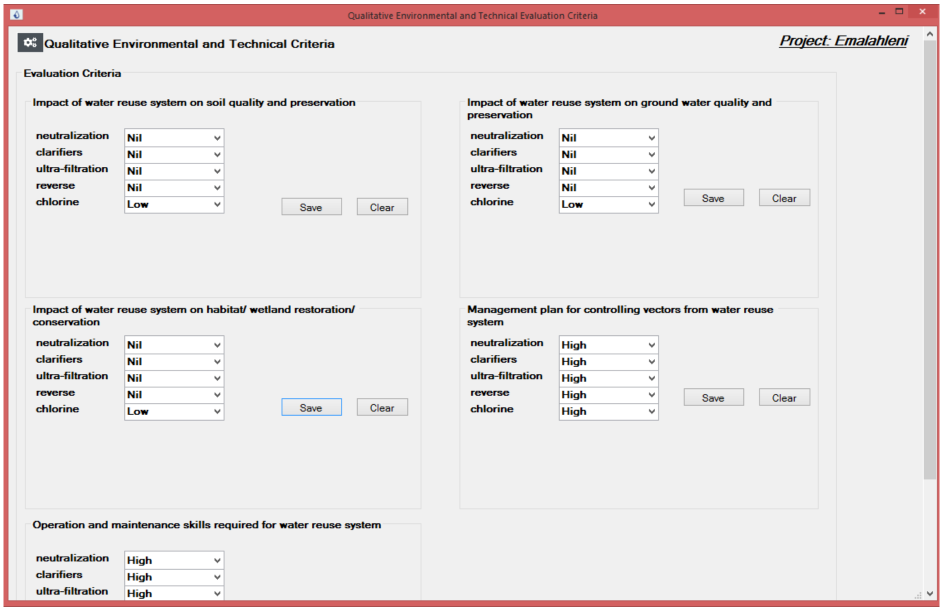
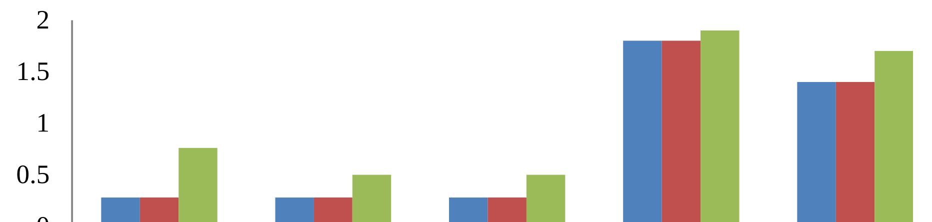


Figure 8.6: Dialog screen for estimating qualitative environmental and technical aspects in the ISI



	EI1	EG1	EN1	EN2	TO1
Emalahleni	0.28	0.28	0.28	1.8	1.4
Hendrina	0.28	0.28	0.28	1.8	1.4
Beaufort West	0.76	0.5	0.5	1.9	1.7

Figure 8.7: Environmental and technical qualitative criteria overall score

8.6.1.2 Quantitative environmental and technical criteria evaluation

Figure 8.9 shows the results of the following quantitative environmental and technical analysis: (i) waste (Sludge) recycling and reuse based on the nutrient and energy value of bio-solid produced from water reuse systems/schemes (EW1), (ii) reliability of water reuse systems/schemes (TR1), (iii) compliance with required standards for physical, chemical and microbial tests performed throughout the year (TP1) and (iv) water quality complaints (aesthetics) e.g., odour, colour, taste (TP2).

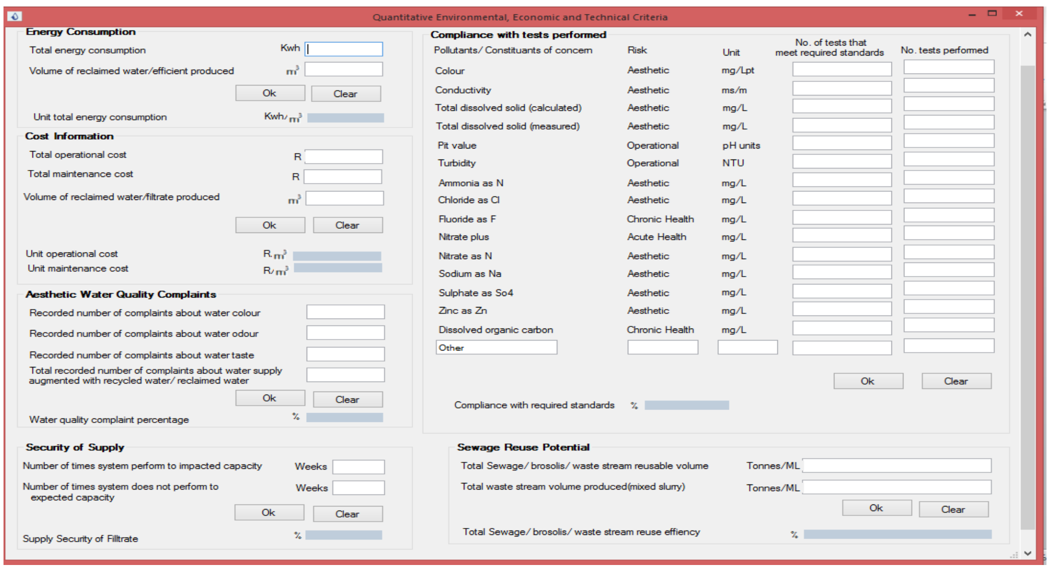
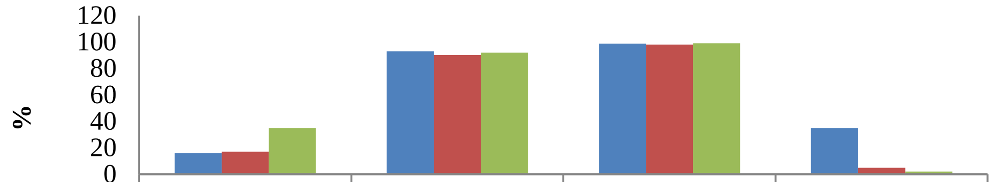


Figure 8.8: Dialog screen for estimating quantitative, economic, environmental and technical aspect in the ISI

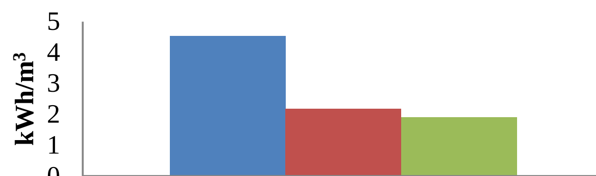
For example, in Emalahleni and Hendrina water reclamations, the sludge reuse potential estimated from plant information provided by plant operators was16% and 17% of mixed slurry produced. The gypsum extracted from the mixed slurry from wastewater treatment production in Emalahleni and Hendrina is often used as part of building construction materials for plastering, bonding, and smoothing of false ceilings. Plant information provided by plant operators in from Emalahleni, Hendrina and Beaufort West water reclamation plants indicated that the plants performed to expected capacity with regards to production of reclaimed water up to 93%, 90% and 96% per annum respectively.



	EW1	TR1	TP1	TP2
Emalahleni	16	93	98.86	35
Hendrina	17	90	98	5
Beaufort West	35	92	99	2

Figure 8.9: Quantitative environmental and technical criteria evaluation score

Plant information provided by plant controllers indicated that Beaufort West, Emalahleni, and Hendrina achieved 99%, 98%, and 98.86% respectively of compliance of reclaimed water with the required standards for physical, chemical and microbial tests performed throughout the year (Figure 8.9). Aesthetic water quality complaints constitute 35%, 5% and 2% of the overall water-related complaints recorded in Emalahleni, Hendrina, and Beaufort West municipalities respectively (Figure 8.9). Figure 8.10 shows that energy intensity of the water reuse systems in Emalahleni, Hendrina, and Beaufort West municipalities is 4.53kWh/m^3, 2.18kWh/m^3, and 1.9kWh/m^3 respectively. Stokes and Horvath, (2009) and Newell et al. (2012) stipulated that energy intensity of the WRSs for direct potable reuse are relatively high in comparison to conventional wastewater treatment plants as the case is in this study.

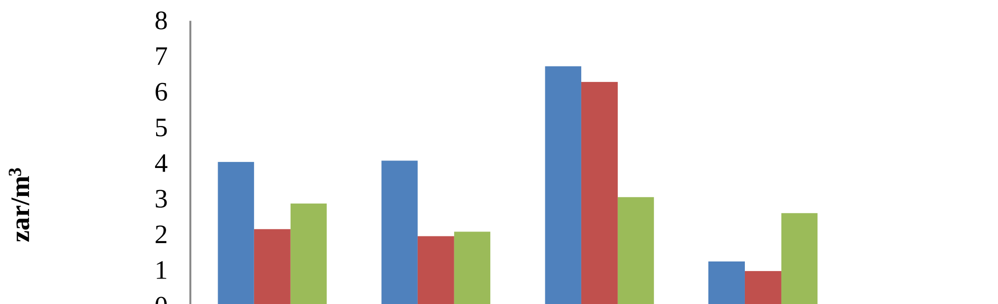


	ER1
Emalahleni	4.53
Hendrina	2.18
Beaufort West	1.9

Figure 8.10: Total energy consumed for production of reclaimed water

8.6.1.3 Economic criteria evaluation

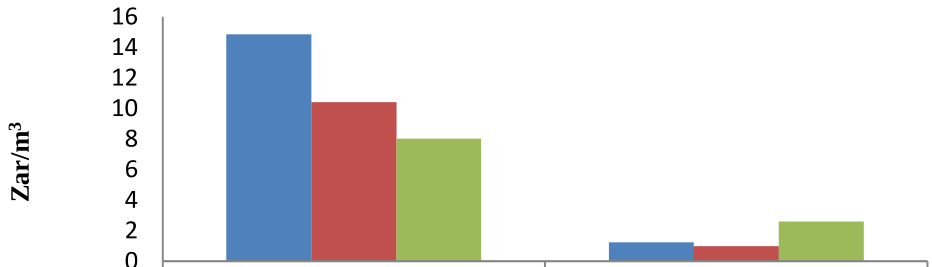
Figure 8.11 shows the results of the analysis of several cost functions used to quantify economic implication of water reuse. In this study, the economic attributes of sustainability of water reuse for potable application was addressed with focus on the cost of operating and maintaining a water reclamation plant (water reuse system). Figure 8.12 shows the (i) unit operational cost **(EL.1)** in Zar/m^3 and (ii) unit maintenance cost **(EL.2)** Zar/m^3. Plant information provided by plants operators was used to estimate the operation and maintenance costs of the water reclamation plants in Emalahleni and Hendrina municipalities (section 6.4.1.2). The operation and maintenance cost for Beaufort West water reclamation plant was adopted from Swartz (2014). Beaufort West water reclamation plant manager cited confidential issue with regards to disclosing 2017 operation and maintenance costs.



	Labour	Energy	Chemicals	Maintenance	Waste management
Emalahleni (Plant A)	4.04	4.08	6.73	1.25	0
Hendrina (Plant B)	2.16	1.96	6.29	0.98	0
Beaufort West (Plant C)	2.88	2.09	3.06	2.61	0

Figure 8.11: Operation and maintenance costs of production of reclaimed water

The cost incurred for waste management and disposal were not included in the analysis due to the lack of plant information. Furthermore, non-recyclable waste products are stored in concrete dam at close proximity to the plants



	EL1	EL2
Emalahleni	14.85	1.25
Hendrina	10.41	0.98
Beaufort West	8.03	2.61

Figure 8.12: Scores for economic criteria

8.6.1.4 Social criteria evaluation

The social aspect assesses the societal impact on the sustainability of reuse for potable application. The results of the social criteria assessment were reported in section 7.2.3 based on the analysis of preliminary questionnaire survey in the case study sites.

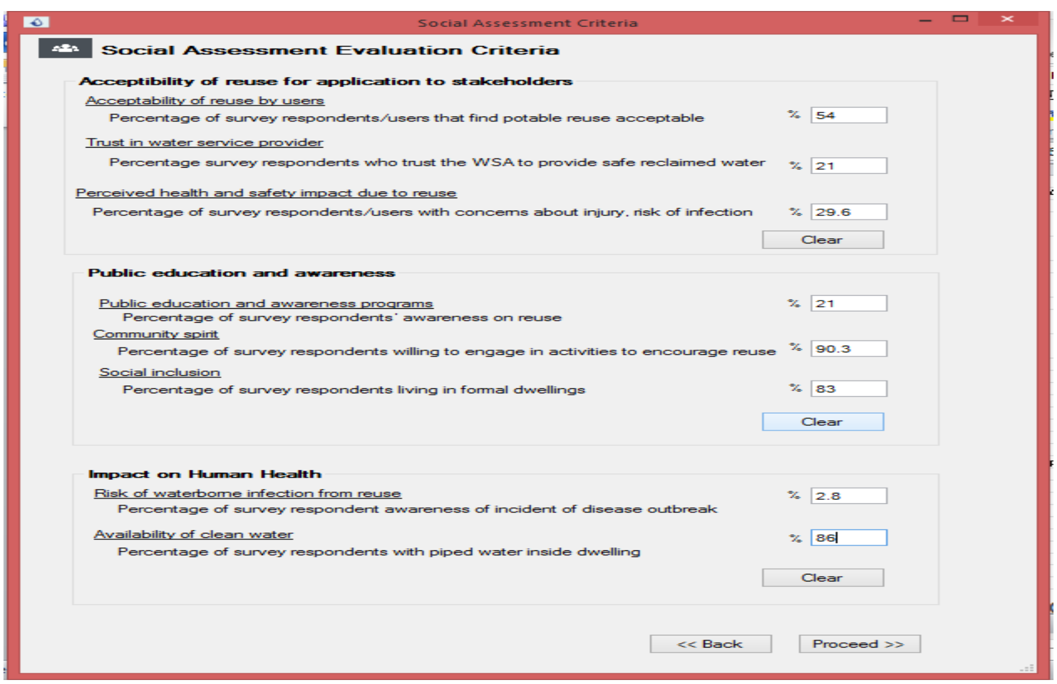
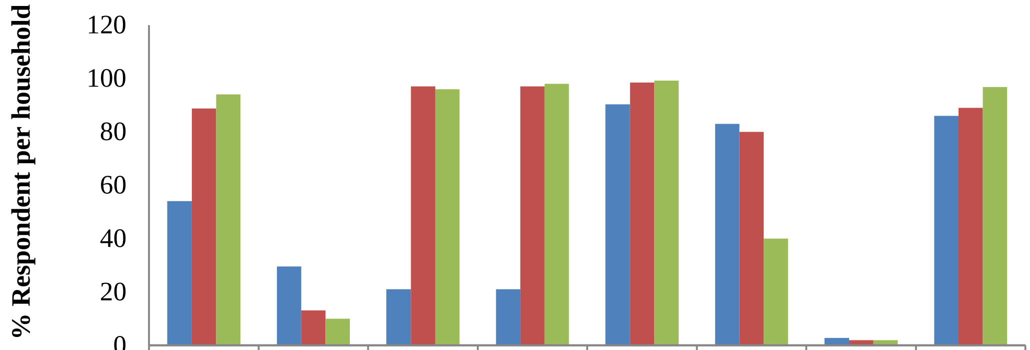


Figure 8.13: Dialog screen for estimating social aspect in the ISI



	SA1	SA2	SA3	SP1	SP2	SP3	SH1	SH2
Emalahleni	54	29.6	21	21	90.3	83	2.8	86
Hendrina	88.8	13.1	97	97	98.5	80	2	89
Beaufort West	94	10	96	98	99.2	40	2	96.8

Figure 8.14: Scores for social evaluation criteria

8.6.1.5 Institutional criteria evaluation

Figure 8.16 shows the relative scores of the institutional assessment criteria. All criteria were assigned a qualitative scores based on experts opinions (Mbokane, pers. comm, 2017; Makgatha, pers. comm, 2017; Marais, pers. comm, 2017) with the exception of the blue drop score. Figure 8.17 shows the blue drop scores for the water reclamation plants in the three case study sites. Appendix 13 illustrates the detailed result of interview with municipal officers and experts regarding the qualitative scores assigned to each qualitative assessment criterion. The blue scores can be accessed in the Department of water affairs' Integrated Regulatory Information System (IRIS)). However, the DWS IRIS is not regularly updated and that have been significant problems in accessing regular Blue Drop reports as well.

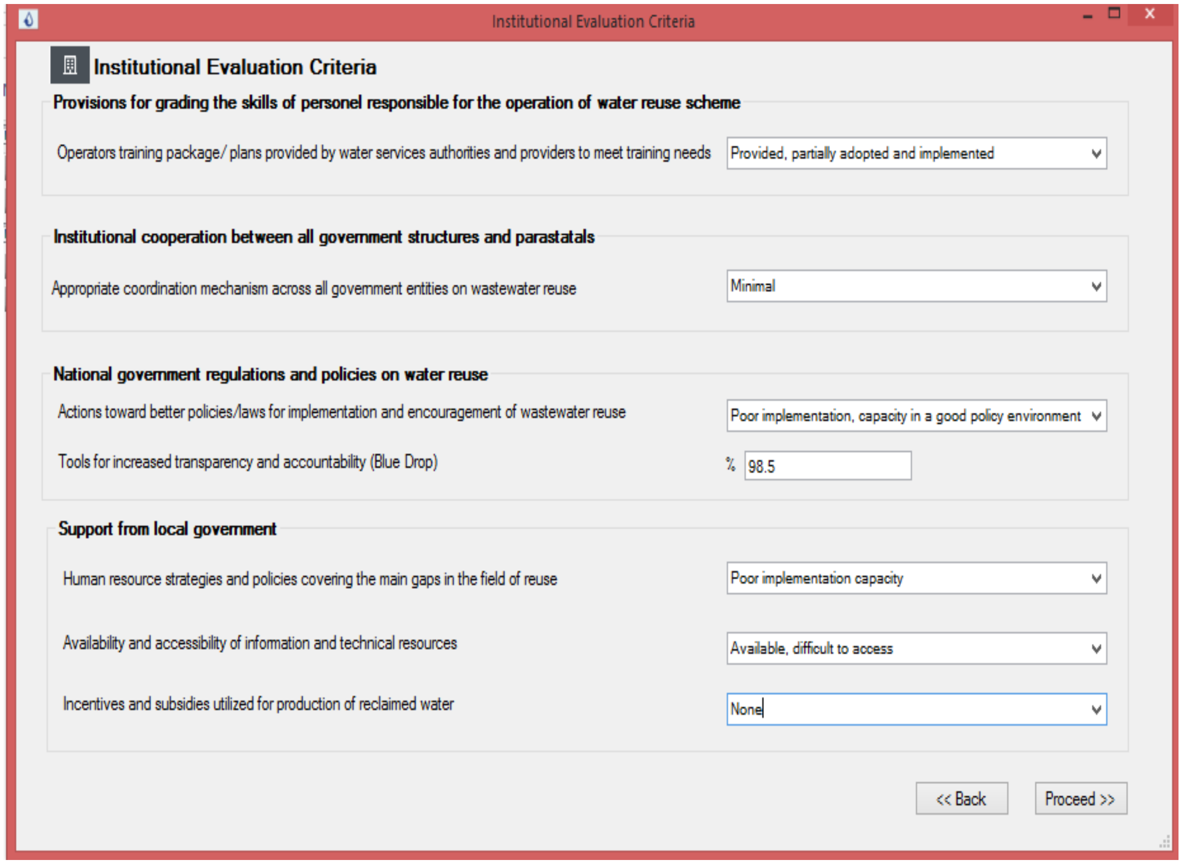
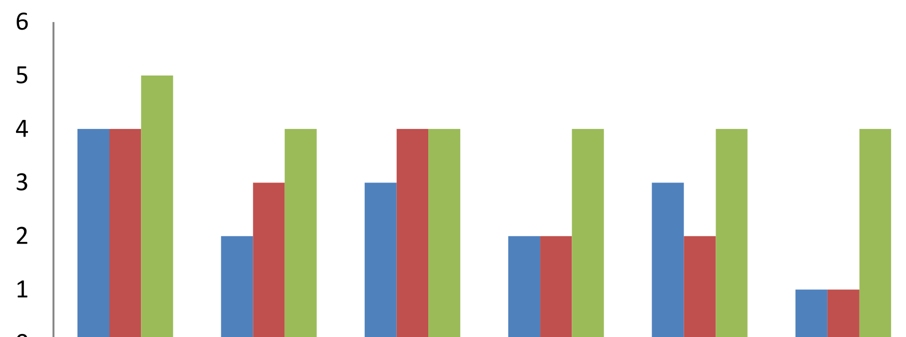


Figure 8.15: Dialog screen for estimating institutional aspect



	IP1	IC1	IN1	IS1	IS2	IS2
Emalahleni	4	2	3	2	3	1
Hendrina	4	3	4	2	2	1
Beaufort West	5	4	4	4	4	4

Figure 8.16: Raw scores for institutional criteria

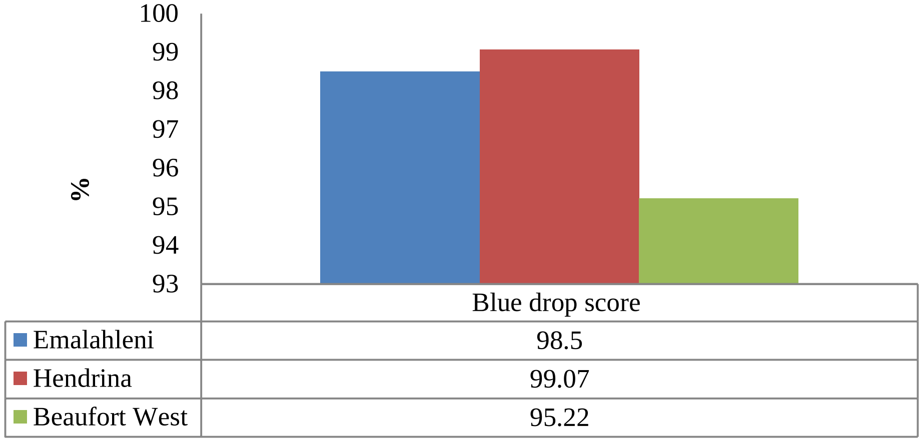
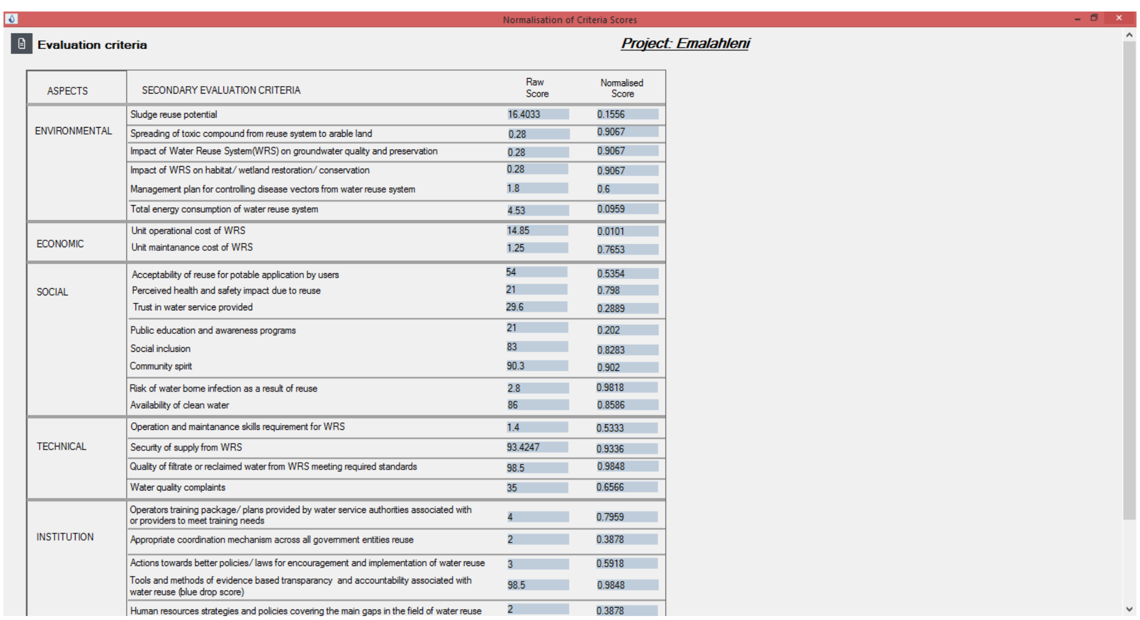


Figure 8.17: Blue drop score (DWA, Integrated Regulatory Information System (IRIS) 2017)

8.6.2 Normalization of the scores for evaluation criteria

As stated in section 4.6.2, the min-max approached was adopted in this study for the normalization of the evaluation criteria. It is imperative to take into consideration the polarity of the criteria.



Normalisation of Criteria Scores

Evaluation criteria

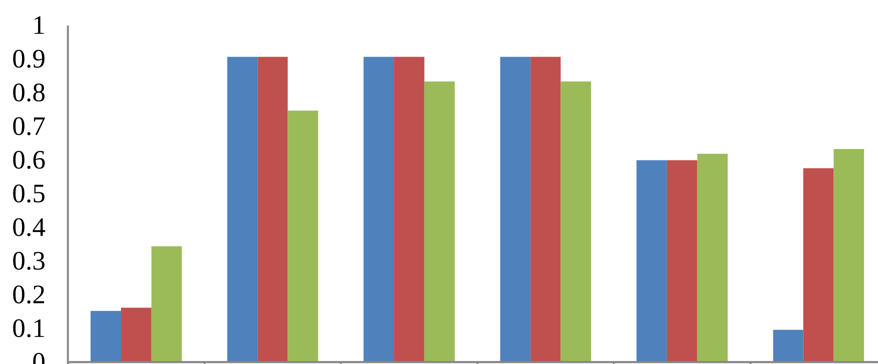
Project: Emalahleni

ASPECTS	SECONDARY EVALUATION CRITERIA	Raw Score	Normalised Score
ENVIRONMENTAL	Sludge reuse potential	16.4033	0.1556
	Spreading of toxic compound from reuse system to arable land	0.28	0.9067
	Impact of Water Reuse System(WRS) on groundwater quality and preservation	0.28	0.9067
	Impact of WRS on habitat/ wetland restoration/ conservation	0.28	0.9067
	Management plan for controlling disease vectors from water reuse system	1.8	0.6
	Total energy consumption of water reuse system	4.53	0.0959
ECONOMIC	Unit operational cost of WRS	14.85	0.0101
	Unit maintanance cost of WRS	1.25	0.7653
SOCIAL	Acceptability of reuse for potable application by users	54	0.5354
	Perceived health and safety impact due to reuse	21	0.798
	Trust in water service provided	29.6	0.2889
	Public education and awareness programs	21	0.202
	Social inclusion	83	0.8283
	Community spirit	90.3	0.902
	Risk of water borne infection as a result of reuse	2.8	0.9818
	Availability of clean water	86	0.8586
TECHNICAL	Operation and maintanance skills requirement for WRS	1.4	0.5333
	Security of supply from WRS	93.4247	0.9336
	Quality of filtrate or reclaimed water from WRS meeting required standards	98.5	0.9848
	Water quality complaints	35	0.6566
INSTITUTION	Operators training package/ plans provided by water service authorities associated with or providers to meet training needs	4	0.7959
	Appropriate coordination mechanism across all government entities reuse	2	0.3878
	Actions towards better policies/ laws for encouragement and implementation of water reuse	3	0.5918
	Tools and methods of evidence based transparancy and accountability associated with water reuse (blue drop score)	98.5	0.9848
	Human resources strategies and policies covering the main gaps in the field of water reuse	2	0.3878

Figure 8.18: Dialogue screen for normalization of criteria scores

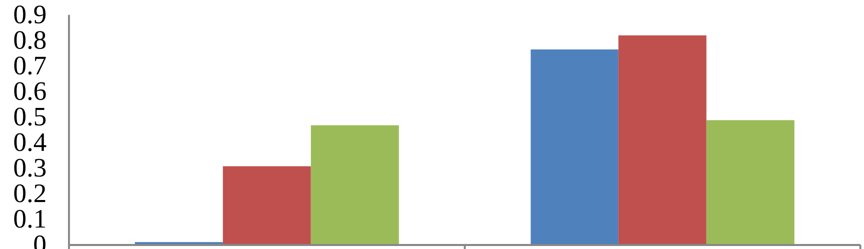
Seventeen sub-criteria have positive polarities (i.e., more is better) and ten have negative polarities (i.e., less is better) (Table 8.7). Expert's opinion and literature reviews were used to establish criteria boundaries. The criteria boundaries serve as the allowable range of values (i.e., the maximum permissible threshold values and minimum permissible threshold values) indicating the performance of the criteria before the normalization exercise. Establishing performance boundaries to evaluate the performance of water in fractures was also employed in the studies by Van der Berg and Danillenko (2011) and Gayllego-Ayala et al. (2014).

The energy intensity boundary of a range of 0.1 to 5kWh/m^3, unit operational cost range from 0.1 to 15 zar/m^3 and unit operational cost from 0.1 to 5 zar/m^3 were adapted from the studies by Stokes and Horvath, (2009), National Research Council (2012), Newell et al. (2012), Yifan Gu et al. (2017), and input from plant operator managers from the three case study sites. Figures 8.19 – 8.20 show the normalized scores of the criteria constituting the ISI.



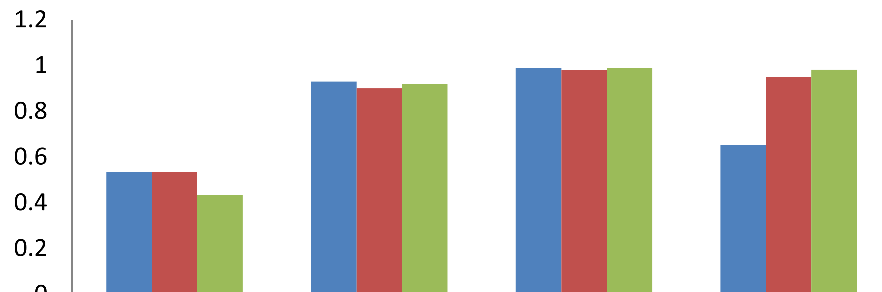
	EW1	EI1	EG1	EN1	EN2	ER1
Emalahleni	0.1515	0.9067	0.9067	0.9067	0.6	0.0959
Hendrina	0.1616	0.9067	0.9067	0.9067	0.6	0.5755
Beaufort West	0.3434	0.7467	0.8333	0.8333	0.619	0.6327

Figure 8.19 Normalized scores of environmental evaluation criteria



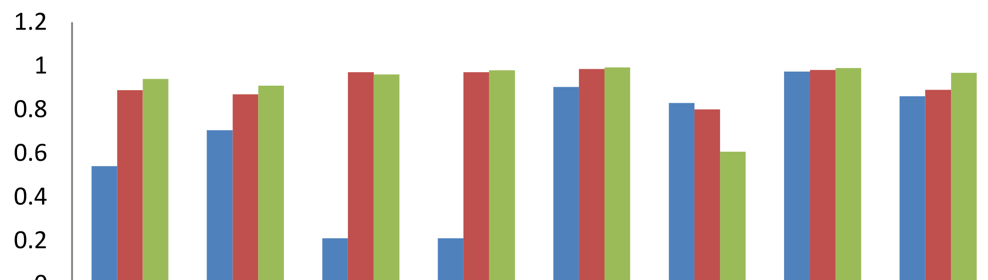
	EL1	EL2
Emalahleni	0.0101	0.7653
Hendrina	0.3081	0.8204
Beaufort West	0.4678	0.4878

Figure 8.20: Normalized scores of economic evaluation criteria



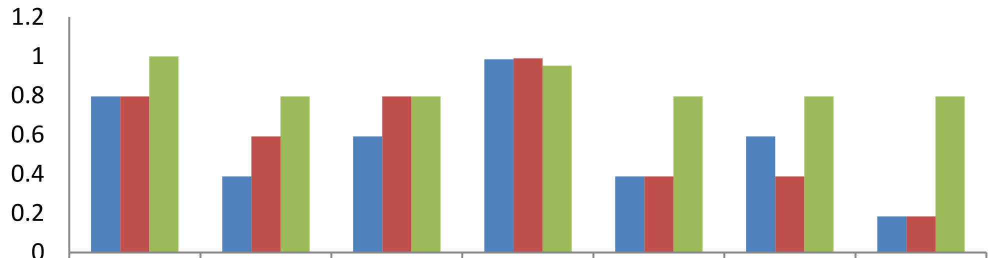
	TO1	TR1	TP1	TP2
Emalahleni	0.5333	0.9299	0.9885	0.6507
Hendrina	0.5333	0.8998	0.9798	0.9509
Beaufort West	0.4333	0.9199	0.9899	0.9809

Figure 8.21: Normalized scores of technical evaluation criteria



	SA1	SA2	SA3	SP1	SP2	SP3	SH1	SH2
Emalahleni	0.5395	0.7047	0.2092	0.2092	0.9029	0.8298	0.9729	0.8598
Hendrina	0.8879	0.869	0.9699	0.9699	0.9849	0.7998	0.9809	0.8899
Beaufort West	0.9394	0.9091	0.9596	0.9798	0.9919	0.6061	0.9899	0.9679

Figure 8.22: Normalized scores for social evaluation criteria



	IP1	IC1	IN1	IN2	IS1	IS2	IS3
Emalahleni	0.7959	0.3878	0.5918	0.9849	0.3878	0.5918	0.1836
Hendrina	0.7959	0.5918	0.7959	0.9906	0.3878	0.3878	0.1836
Beaufort West	0.9999	0.7959	0.7959	0.9522	0.7959	0.7959	0.7959

Figure 8.23: Normalized scores for institutional evaluation criteria

The next step in the assessment process is the attribution of weights and aggregation into a single unit.

8.6.3 Weighting and aggregation

In this study, we considered using the equal weighting technique and assigning of weights using expert opinion (normative approach OECD-JRC, 2008) for assigning weights to the primary and secondary criteria. However, due to subjectivity of the later approach we decided to use the equal weight technique.

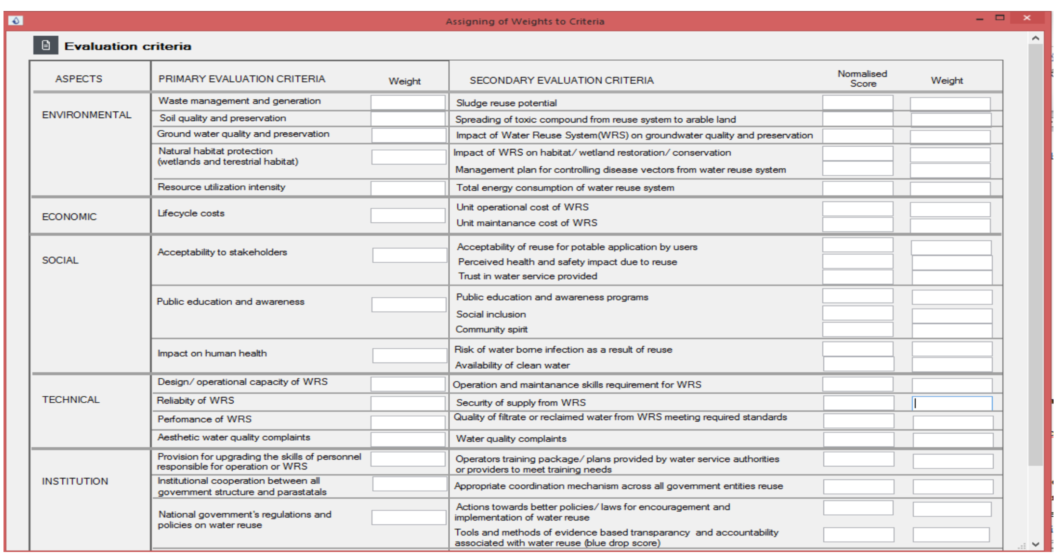


Figure 8.24: Dialogue screen for assigning of weight and aggregation of normalized criteria scores

Further analysis using the two aforementioned indicator weighting techniques found a slight variation in the index score level and dimension score level. The results of the overall scores at the index level indicate maximum deviations of 0.075 for Emalahleni, 0.05 for Hendrina and 0.007 for Beaufort West respectively. The ISI falls under the same category with the Environmental Sustainability Index (ESI) developed Esty et al. (2005) and the Sustainability Index for Integrated Urban Water Management (SIUWM) developed by Carden (2013) that strongly advocate the use of the equal balanced weighting technique. The decision to use the equal weight technique was further amplified because the qualitative environmental and technical treatment train scores and the Blue drop scores used in the analysis are already weighted and consolidated into a final unit score per criterion (Appendix 9 in Excel spread-sheet enclosed in CD labeled appendices).

According to Bohringer and Jochem (2005), aggregation of values using the geometric mean approach has the tendency to diminish the effect of the numerical gap between high and low values which might result in a bias mean if the linear arithmetic aggregation method is used. Hence, we employed the use of the weighted geometric mean aggregation technique for the aggregation method for the ISI calculations. However, the ISI is designed in such a way to assigning and change weighting alternatives at different steps of the analysis in order to observe the impact it will have on the aggregated index if needed. Table 8.10 and Figure 8.25 provide comparative results for the five different sustainability dimensions scores for the selected case study sites.

Table 8.10: ISI scores for case study sites using equal weighting approach

	Case study sites		
Dimensions	**Emalahleni**	**Hendrina**	**Beaufort West**
Environmental	0.5946	0.6762	0.668
Economic	0.3877	0.5643	0.4778
Technical	0.7756	0.8409	0.831
Social	0.6535	0.919	0.9179
Institutional	0.5343	0.5905	0.8473
ISI score	0.5891	0.7182	0.7484

It can be deduced from the scores of the sustainability dimensions that economic dimension fares the worst with an average score of 0.4756 across the of the three case study sites. Hence, it appears that economic criteria contribute to challenges impeding the transition towards a sustainable state.

8.6.4 Individual sustainability dimension scores

As shown in Figure 8.25, there some similarities in the ISI scores between Hendrina (further inland) and Beaufort West, although both municipalities are located at different province within the country. The same cannot be said for Hendrina and Emalahleni which are within the same province. Nonetheless, one of the primary objectives of this study was to develop an index that is relevant to assessing the sustainability of reuse at different scale and geographical location. Table 8.10 depicts the characteristic strengths and weaknesses in the general assessment of water reuse sustainability in three South African communities, as well as their performance across each sustainability dimension.

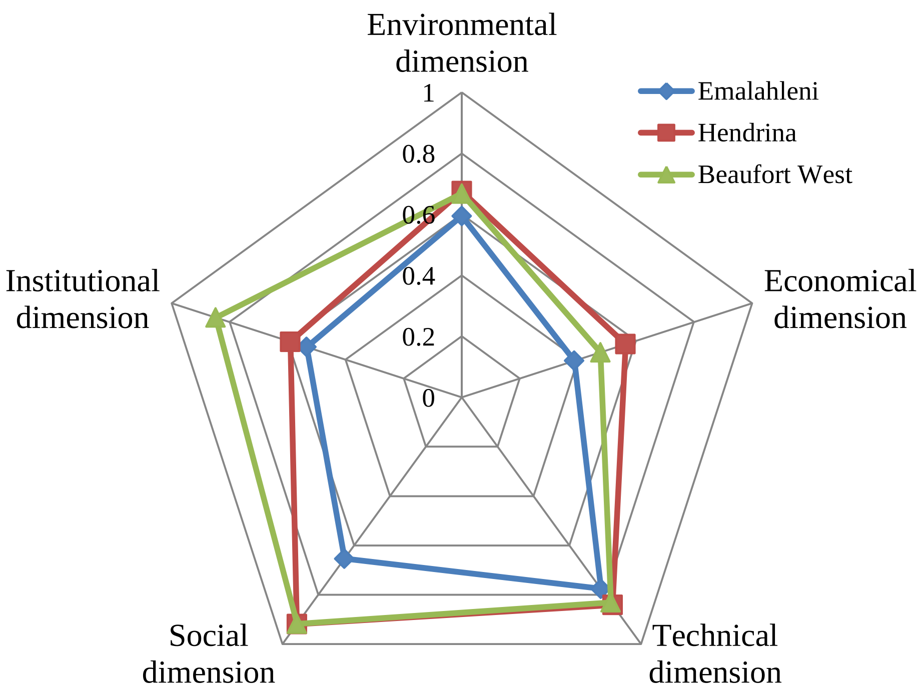


Figure 8.25: Comparative indicator performance for Emalahleni, Hendrina and Beaufort West using equal weighting approach

The result of the individual dimension analysis shows that Beaufort West has the highest scores of 0.9179 and 0.8473 in social and institutional dimension respectively in comparison with Hendrian and Emalahleni. Beaufort West municipality has a history of water scarcity due to drought conditions as reported in the municipality's water service development plan of 2010 (BWM, 2010). With the inception of the reuse initiative in the year 2011as a palliative measure to tackle water supply challenges, hence, this result is expected. The result of the social dimension validates the efforts on the part of the municipal authorities through several public awareness programs and publications in local papers in reaching out to users to embrace reuse for potable application. Holloway et al. (2012) in their study describes some of these public awareness programs employed by the Beaufort West municipal authorities to educate the public on reuse. A satisfactory score of 0.919 in social dimension analysis was recorded for Hendrina as well with a moderate score of 0.635 recorded for Emalahleni. Hence, in Emalahleni resources must be allocated to educate the public on reuse.

Further analysis indicates that the relative strength of the three case study sites lies in the technical dimension, with score of 0.7756, 0.8409 and 0.831 for Emalahleni, Hendrina, and Beaufort West respectively. On the other hand, economic dimension contributes the least to the overall scores of the case study sites, with scores as low as 0.3877, 0.5643and 0.4778 in Emalahleni, Hendrina and Beaufort West respectively. The disparity in scores for Emalahleni, Hendrina and Beaufort West can be attributed to the following differences between the three case study sites:

- **Social dimension**

Effort should be invested in long-term strategies for creating awareness on reuse among the public in Emalahleni on reuse (Holloway et al. 2012). In Emalahleni, establishing an effective and efficient communication channel between the public and the water service authorities can further enhance the credibility and trust in water services authority (Ross et al. 2014).

- **Economic dimension**

Exploring of alternative cost opportunities to mitigate cost implications of reuse. Exploring opportunities to lower the operation and maintenance costs expended for the production of reclaimed water is applicable to three case study sites but most importantly Emalahleni. Operation and maintenance costs have a significant bearing on the price of reclaimed water and cost of production as well (Ruiz-Rosa et al. (2016).

- **Technical dimension**

Exploring opportunities for energy substitutions and potential reuse of the waste-stream generated from reclaimed water production

- **Institutional dimension**

Provision of incentives and subsidies on the resources utilized for the production of reclaimed water on the part of the Emalahleni and Hendrina municipal authorities. Beaufort West municipal authority is billed directly for electrical energy utilized by the water reclamation plant (Naroth 2016). This is not the case in Emalahleni and Hendrina. There is the need for improvement on the relative economic standing on the part of the municipal authorities in Emalahleni and Hendrina as an indication of their commitment to encouraging the sustainability of reuse initiatives. Secondly, the existence of a supportive political environment that facilitates appropriate coordination across all government entities on reuse. Furthermore, the existence of better laws and policies to encourage implementation of mitigation measures to enhance reuse initiatives. Furthermore, the existence of supportive political structures that encourages institutional capacity, manage human and technical resources needed to address the challenges facing water reuse sustainability.

8.6.5 Overall ISI scores

The overall range of the ISI assessment scores for the case study sites– Emalahleni, Hendrina, and Beaufort West municipalities are displayed in Figure 8.26. Beaufort West municipality has the highest score of 0.7484, followed by Hendrina municipality with a score of 0.7182 and Emalahleni municipality with the lowest score of 0.5891. However, a closer look at the results of the ISI clarifies the reasons for the poor performance in some of the sustainability dimensions as highlighted in results of evaluation of sub-criteria that are the building blocks of the index (see figures 8.7, 8.9, 8.11, 8.12, 8.14, 8.16 and 8.17). The results of the water reuse sustainability assessment in the case study sites using the ISI attest to the robustness of the ISI as a decision support tool that provides valuable analysis that is more than just an assessment of the performance in specific areas of water reuse. The classification depicted in Table 8.11 signifies the anticipated ISI results from a range of criteria scores. A score that falls within the range of values for the red classification is interpreted as "no potential for sustainability" under the current conditions or current practices of water reuse initiative within the period the assessment was carried out. An ISI score for a water reuse scheme for potable applications that falls within the range of values for the color green classification is said to have a "considerable potential for sustainability". However, an ISI score that falls within the color green category does not necessarily signify the absence of weakness/vulnerabilities, but a progressive effort towards a sustainable state. The orange and yellow classifications depict situations where the current practices and state of water reuse scheme are starting to facilitate moves towards a sustainable state.

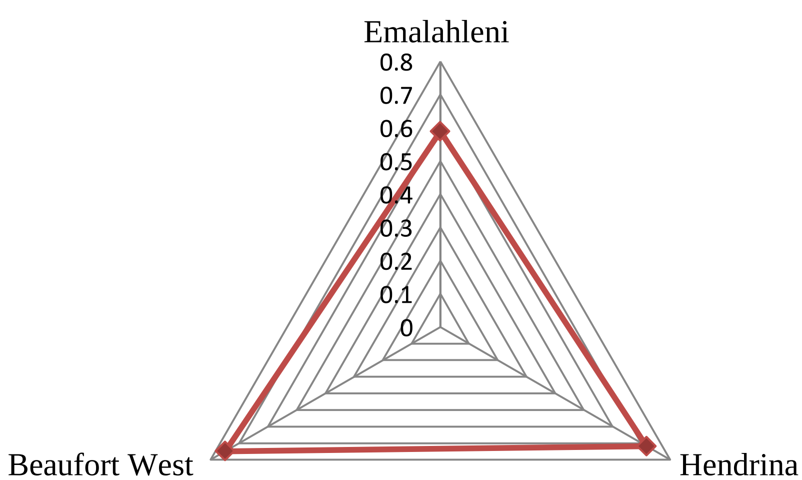


Figure 8.26: ISI scores for the three case study sites

The colors depicting the ISI scores indicate a snapshot of the progress towards achieving the goals of sustainable development with respect to water reuse for potable applications. The divisions and color classification interpretation adopted in this study were determined based on the review of studies by Carden (2013) and Gallego-Ayala (2014), result comparison with sustainability targets and criteria scoring method described in Appendix 12. The classification shown in Table 8.11 signifies the expected ISI results from a range of criteria scores.

This study adopted the use of the "traffic light" analogy used in the study by Carden (2013) for the pictorial representation and straightforward interpretation of the of the ISI scores. Table 8.12 categorizes the range of ISI scores into an easy-to-understand 'traffic light' analogy, which has been used to characterize the case study cities for the current assessment with regards to Table 8.11.

Table 8.11: Traffic light analogy for classifying ISI scores (adapted from Carden 2013)

Category	ISI score	Interpretation
	0 - 0.30	no potential for sustainability
	0.31 – 0.60	low potential for sustainability
	0.61 – 0.75	reasonable potential for sustainability
	0.76 - 1	considerable potential for sustainability

The overall score of the ISI provides an insight into the potential for water reuse sustainability towards the goal of sustainable and can be used to benchmark a community against another. The individual criterion making up the ISI provide an indication of the contributing factors to water reuse sustainability and highlights the areas where there are rooms for improvement. The ISI identifies the strength and weakness in achieving a sustainable water reuse initiative in the case study sites allowing stakeholders to prioritize actions to improve water reuse sustainability for potable applications. Furthermore, the ISI can be a decision support tool for human and financial resource allocation to prioritize interventions in cities with low ISI scores. As expected based on the challenges that have been highlighted – Emalahleni municipality falls into the category of "low potential for sustainability" at the period the assessment was carried as depicted in Table 8.12. On the other hand, Hendrina and Beaufort West municipalities falls under the category of "reasonable potential for sustainability" at the period the assessment was carried out (Table 8.12).

Table 8.12: ISI scores for case study sites

Municipality	ISI score	Category	Measure of sustainability
Emalahleni	0.5891		low potential for sustainability
Hendrina	0.7182		reasonable potential for sustainability
Beaufort West	0.7484		reasonable potential for sustainability

This pictorial representation of the sustainability assessment analysis is therefore capable of highlighting the features of water reuse initiative that may have an impact on its capability to maintain and make progress towards a more sustainable state. This assessment exercise must be carried out repeatedly over a specific time frame (annually, biennially) by way of comparisons of community's results to indicate any real progress towards a sustainable state (i.e. a sustainable state where adequate supply of good water quality is maintained for the entire population, while preserving the hydrological, biological and chemical function of the ecosystems, adapting human activities within the capacity limits of nature and to combat vectors of water-related diseases (Mihelcic et al. 2003).

8.7 Summary

This study presents an innovative and holistic indicator for assessing the sustainability of water reuse for potable applications in SA communities. The application the ISI to Emalahleni, Hendrina and Beaufort West municipalities showed the tool to be a robust tool which provides a proper assessment of both qualitative and quantitative criteria in the evaluation of water reuse for potable applications. The developed ISI efficiently assess the sustainability of water reuse for potable applications from a holistic perspective in three case studies in SA. The ISI contributes to the effort to assist decision makers concerning intricate and multidimensional decision-making challenges, such as assessing the sustainability of reuse as an alternative water management strategy. Moreover, the consolidation of a set of sustainability assessment criteria into a single unit component prospectively can improve the dissemination, interpretation, and understanding of sustainability information to all stakeholders.

CHAPTER 9

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Thesis Summary

SA is a water-scarce country, challenged with transforming its unsustainably resource-intensive economy at the same time addressing the effects of apartheid as well (DWA, 2013). The equitable and uninterrupted supply of adequate water to South African citizenry is one of the most major challenges facing the country. According to Muller et al. (2009), in order to avert water crisis, existing water resource systems will need to be managed effectively in term of quantity of resources as well as quality. The need to explore alternative water management strategies cannot be over emphasized. The rapid growth in population, increasing affluent lifestyles, urbanization and industrialization are major factors putting severe strain on the availability of freshwater supply. It is evident that alternative, systems-based approaches to conventional water management of water supply and modes of ensuring water quality are required (Armitage et al. 2014).

Over the past thirty decades, alternative water management strategies such as water reuse have been implemented across the globe to mitigate the challenges facing reliable potable water supply to meet demand. Water reuse is an established alternative water management strategy that possesses a significant potential to alleviate the challenges facing water supply meeting demand overtime. It is evident from the discussion in chapter one that water reuse for potable applications is a viable alternative water management strategy to tackle and alleviate the challenges facing water supply security in water scarce regions across the globe. In light of this, there is need to develop tools that will aid decision making when assessing critical factors governing water reuse sustainability. The aim of this research was to develop a decision support tool for assessing the sustainability of water reuse for potable applications in South African communities.

A detailed investigation should be carried out to address the challenges facing the long term sustainability of water reuse for potable application from a multidisciplinary perspective, taking into consideration economic, institutional, technical, environmental and social features of existing and proposed water reuse initiatives. All these features contribute to the success and sustainability of any water reuse initiative and their thorough scrutiny will facilitate making a reliable decision. The ISI as a decision support tool achieves a balance between the social, technical, economic, institutional and environmental dimensions involved in assessing the sustainability of water reuse for potable applications. The flowchart representing the layout of this thesis is shown in Figure 9.1.

Chapter 2 fulfills objective number one of this research. Chapter 2 begins with an introduction to the concepts of sustainability in UWM practices. The concept of urban water management was discussed as well as the definitions of conventional urban water systems and alternative urban water systems. Urban water management strategies such as IWRM, WSUD, UWSS, and water reuse were discussed. Furthermore, chapter 2 discusses sustainability and sustainable development (SD). SD as defined by Becker (1997) and Sahely et al. (2005) is attaining a balance between three main goals: social, economic and environmental, across both spatial and temporal perspectives. The quantitative and qualitative assessment of sustainability/SD has always been a challenge. Hence, the need for the development of appropriate indicators to evaluate the sustainability assessment process.

Indicators or indices are assessment criteria that seek to identify underlying principles to determine if the set goals and objectives were achieved. The assessment criteria are used to establish a yardstick to which sustainability objectives are measured against. Examples of sustainability assessment framework include: MFA, LCA, objective oriented framework, sustainability dimensions, process driven approach and linkage based framework. These sustainability assessment frameworks are discussed in details in chapter 2.

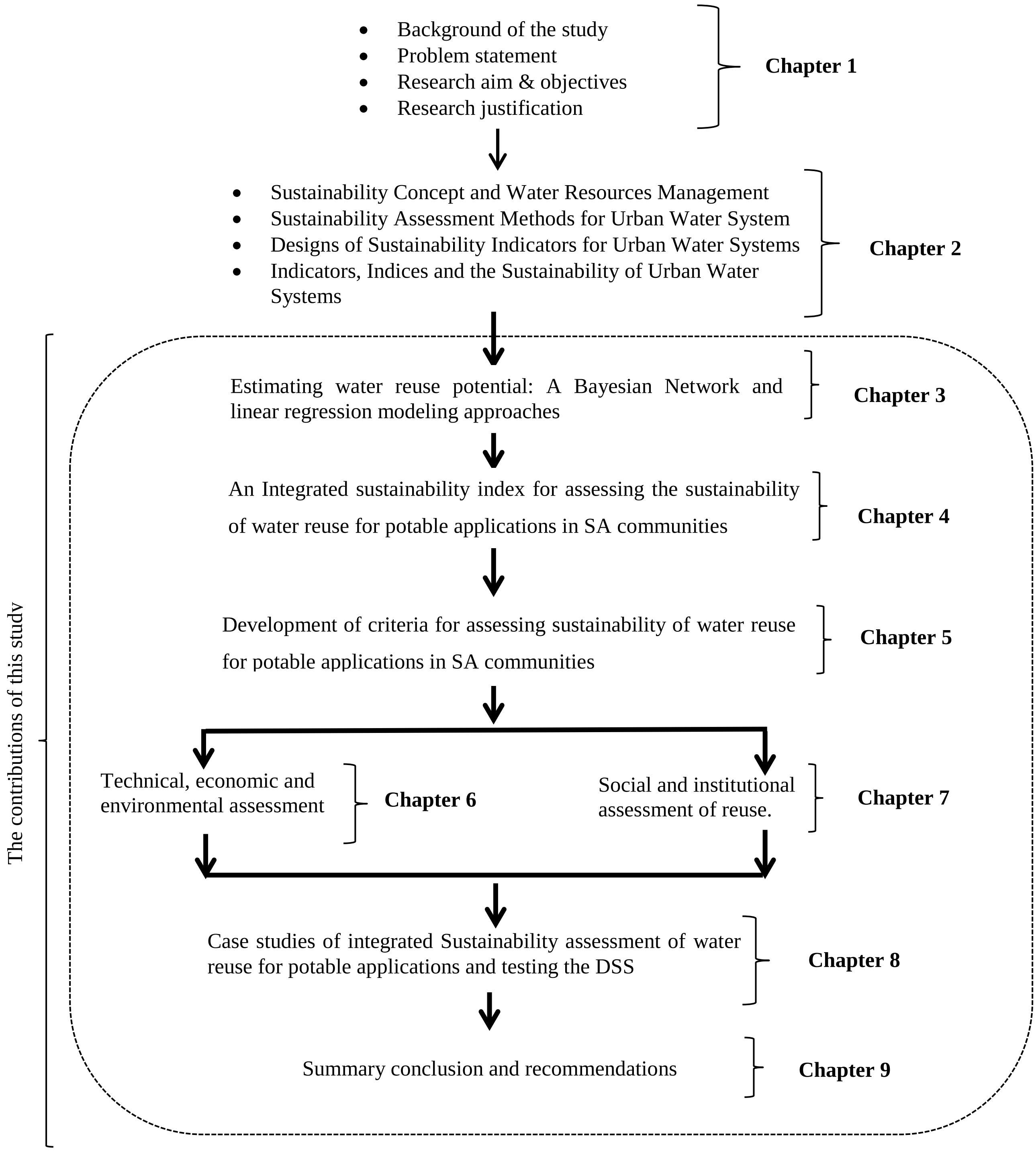


Figure 9.1: Flow chart of the dissertation layout

The methods for assessing sustainability such as LCA, MRA and MCA were considered as well. Implementation and experiences of sustainable urban water management practices such as SWITCH, integrated resource planning and the soft path of water were discussed with location where these practices have been implemented. The chapter highlighted and discussed issues that need to be addressed with regards to sustainable urban water management such as (i) climate change effect on urban water systems, (ii) the need for paradigm shift in tackling the problem of sustainability and (iii) capacity development in private organizations, society and institutions (government, academic).

Taking into consideration the several alternative water resources management strategies, the reason to implement any form of reuse must be justified. It is imperative to provide scientific evidence to justify the need for reuse and the potential reuse possesses to contribute to the solution to water scarcity problems. Hence, this study developed (i) linear regression models and (ii) Bayesian Network models for predicting the usable return flow from two main wastewater streams (i.e. agricultural and urban (domestic and light industries) sectors) in SA. The two models with reasonable accuracy can predict usable return flow that can be treated and used for other beneficial applications. The study contributes to knowledge by developing a methodology that is cost effective, accessible and transparent to support and quantitatively justify reuse as a potential alternative water management strategy to combat water scarcity. Establishing the need for reuse and justifying the need for reuse is an important step towards implementing water reuse systems. Chapter 3 fulfills objective number 2 of this research (and thus presents an original contribution to knowledge) by the development and application of a linear regression model and Bayesian Network model for predicting usable return flow from agricultural and urban activities in South African water management areas. The results of the correlation analysis showed that URFA is highly correlated with AWU and WU. Although the correlation between SPI and CIW with WU and AWU is low, their correlation with URFA is negative as expected. The results of the models in this study show that about 8% of the agricultural water use is potentially reusable while about 34% of the total domestic water use is potentially reusable.

Upon development and establishment of water reuse systems, there is need to evaluate the sustainability of these systems overtime as well as the contribution of these systems to overall objectives of sustainable development. Hence, this study developed a framework for the assessment of water reuse sustainability for potable applications in SA communities. This study research took the concept of soft systems thinking approach a step further by the development of a framework for assessing water reuse sustainability which incorporates criteria development and selection using expert opinion with knowledge on reuse. Chapter 4 fulfills objective number 4 of this research (as a contribution to knowledge). Chapter 4 presented a review of the concept of integrated assessment of water reuse sustainability and the existing sustainability assessment frameworks such as TBL, PSR, and DPSEEA, Furthermore, chapter 4 entails the adapted theoretical framework for the development of the ISI and the explanation of the sequence of steps involved as well. The proposed framework integrated the stakeholder's participatory approach and DPSEEA frameworks for the carrying out the sustainability assessment process. The framework was adapted from the five-level model coupled with the step-wise methodology proposed by Nardo et al. (2008) and the OECD (2008) methodology for the development of composite indicators as it provides a comprehensive approach for the construction of an index. The framework entails the approach for the development and selection of criteria used for the sustainability assessment process, the explanation of sequence of steps that led up to the ISI score. These steps include: data selection, normalization, weighting and aggregation. The assessment techniques relevant to each step that was employed in this study were also discussed. Such techniques include normalization: min-max approach; weighting: equal weighting technique and aggregation: geometric aggregation technique.

Assessing sustainability of water reuse schemes involves a multidisciplinary approach that incorporates technical, economic, environmental, institutional and social factors. The starting point is the identification, development and selection of criteria that cut across five attributes of sustainability for the assessment process. This study, based on consultation with experts in the SA with knowledge on reuse to developed criteria for a holistic assessment of water reuse sustainability in South African communities. This contributed to the robustness of the ISI as a DSS developed in this study. Chapter 5 fulfills objective 3 of this study (hence, it presents an original contribution to knowledge). Chapter 5 entails the development and selection of criteria that are the building blocks of the ISI. A set of twenty-two primary criteria and fifty-three secondary criteria were developed for the sustainability assessment process. Experts in South African water sector (with knowledge on reuse) were consulted to harmonize the developed criteria and determine their importance to the sustainability assessment process in a South African context. The set of criteria for the assessment process were harmonized from twenty-two primary criteria to sixteen primary criteria and fifty-three secondary criteria to twenty-seven secondary criteria based on the consultation with the experts. These selected criteria are representative of the five sustainability dimensions (economical, technical, environmental, social and institutional). A full detail of these criteria and method of measuring them was presented in appendix 13.

Furthermore this study developed quantitative and qualitative assessment methodologies to evaluate the criteria that cut across the aforementioned sustainability dimensions. Chapter 6 fulfills objective number 5 of this research (hence, it presents an original contribution to knowledge). Chapter 6 explains the various criteria constituting the technical, environment, economic dimensions of the ISI. It explains the framework for the development of the ISI into a decision support tool using the multi-criteria methodology. The framework provides a robust structure for assessing water reuse sustainability, thereby providing relevant stakeholders and decision makers an essential tool with quantitative and qualitative assessment criteria that cut across the aforementioned sustainability dimensions. Chapter 6 begins with the approach adopted for estimating water saving potential due to reuse of reclaimed water for potable applications. This estimation of water saving potential due to reuse justifies a water reuse initiative by providing the volumetric portion of potable water supply that can be covered by reclaimed water.

The technical, environmental and economic criteria used for evaluating WRSs were based on consultation with experts. The quantitative environmental criteria are (i) sludge reuse potential and energy intensity of the treatment technology. As part of the quantitative assessment methodology, an activity based energy utilization (ABEU) model and a cost analysis model were developed and applied to evaluate energy intensity and operation and maintenance cost respectively. The ABEU model was applied to water reclamation plants for potable applications in Emalahleni and Hendrina municipalities. The qualitative environmental criteria considered include: impact of WRSs on soil quality and preservation; (ii) impact of WRSs on groundwater quality and preservation; (iii) management plan to control disease vectors from WRSs, and (iv) impact of WRSs on habitat conservation/restoration**.** The qualitative technical criterion considered in this study is the operation and maintenance skill requirements for WRSs. An integrated cost analysis model was developed and applied to two water reclamation plants for potable applications in Emalahleni and Hendrina municipalities for the assessment of the economic criteria: operation and maintenance costs.

Community acceptance is a critical factor (which falls under social attribute of sustainability) that affects the successful implementation and sustainability of water reuse for potable application overtime. Chapter 7 fulfills objective number 5 of this research (hence, it presents an original contribution to knowledge). Chapter 7 contains the methodology for the social and institutional assessment adopted in developing the social and institutional module of the ISI. A hypothesized model was developed to investigate the factors influencing acceptability of reuse for potable applications. The model was used to validate the impact of the social criteria (such as trust in water service authority, knowledge of reuse benefits, health risk perception etc. which were included in the DSS) on the intention to accept reuse for potable applications. Eleven hypotheses were tested using this hypothesized model with regards to reuse for potable applications. The result of the study shows that in Hendrina municipality, knowledge of reuse benefits had an indirect negative effect on intention to accept reuse for potable applications through health risk perception (R^2=-005). This implies that health risk perception reduces the direct impact on knowledge of use benefit on behavior by 0.5%

of the total variance. This is also applicable to the indirect effects of subjective norm (R^2=-007) and the use history of water to be reclaimed on intention to accept reuse for potable applications (R^2=-.011). On the other hand, the indirect effect of public awareness on behavior through health risk perception was significant and positive; R^2=-005). This implies that health risk perceptions increase the direct effect of public awareness by 0.05 units on intention to accept reuse for potable application.

In Emalahleni municipality, the following variables had significant indirect effects through health risk perception: knowledge of use benefits (R^2=0.014), subjective norm (R^2=0.002), the use history of water (R^2=0.004), public awareness (R^2=-0.001), and trust in WSA (R^2=-0.008). This implies that the indirect effects of knowledge of reuse benefits, subjective norm and the use history of water through health risk perception is lower than the direct effect each of the independent variables have on the intention to accept reuse for potable applications. It is important to note that the indirect effects identified were positive, knowledge of reuse benefits (1.4%), subjective norm (0.2%) and the use history of water (0.4%). On the other hand, the indirect effects of public awareness (-0.1%) and trust in the WSA (-0.8%) had negative indirect effects through health risk perceptions on intention to accept reuse. Hence, reducing the total effect of these variables on intention to accept reuse for potable applications.

In the Hendrina municipality, only credibility of WSA had a significant positive indirect effect on behavior through trust and health risk perception respectively. This implies that the direct effect of credibility of WSA on behavior is enhanced by trust and health risk perception. In the Emalahleni municipality, the following variables, procedural fairness (R^2=0.039), shared values (R^2=0.020), group membership (R^2=0.181), credibility of WSA (R^2 =0.180) and environmental justice (-0.090) had significant indirect effect on acceptability through health risk perception. The indirect effects through health risk perception of group membership (18.1%) and credibility of WSA (18.0%) were higher than the direct effects of each of the variables on acceptability. This indicates that the mediating effect of health risk perception and trust in WSA on acceptability increased the total effects of the two variables. It is easy to infer that the effect of group membership and credibility of WSA on acceptability is better when health risk perception and trust mediates than when they are acting directly on acceptability.

The indirect effect of procedural fairness (3.9%) and shared values (2.0%) through trust in WSA and health risk perception were also positive but lower than the direct effect. On the contrary, the indirect effect of environmental justice through trust and health risk perception is negative (-9.0%) and it is also higher in magnitude than the direct effect of environmental justice when it considered directly on acceptability.

Finally, the developed ISI was used to assess the sustainability of water reuse for potable applications in Emalahleni, Hendrina and Beaufort West municipalities. Chapter 8 fulfills the objective 7 by testing the ISI (a novel indicator, hence an original contribution to knowledge). Chapter 8 begins with a brief description of the ISI structure. The ISI was developed using a C-Sharp programming language. The ISI was designed as an interactive software with a user friendly interface for logging in information, processing of the information and generating an outcome as a result. The modules making up the ISI are:

1. General information module (community name, water management area, province and population)
2. Water saving potential estimation module
3. Treatment train selection module
4. Qualitative environmental and technical criteria evaluation module
5. Quantitative environmental, technical and economic criteria evaluation module
6. Social criteria evaluation module
7. Institutional criteria evaluation module
8. Score normalization module
9. Aggregation module

The application of the ISI to assess the sustainability of water reuse for potable applications in Emalahleni, Hendrina and Beaufort West municipalities showed the tool to be useful and provide a good of qualitative and quantitative criteria of sustainability dimensions. The result of the water saving potential estimation model (built on a modified mass balance approach) indicate that by reusing treated wastewater, potable water demand in the Emalahleni, Hendrina, and Beaufort West can be reduced by 22.8 %, 47.3% and 29.3% respectively. The overall range of the ISI assessment scores for the case study sites-Beaufort West, Hendrina and Emalahleni, municipalities are 0.7484, 0.7182 and 0.5891 respectively. As expected, based on the discussion in section 8.6.4 – Emalahleni municipality falls into the category of "low potential for sustainability" at the period the assessment. On the other hand, Hendrina and Beaufort West municipalities falls under the category of "reasonable potential for sustainability" at the period the assessment was carried out. From the results of the study, the ISI as a DSS tool measures sustainability performance of water reuse schemes in SA communities successfully. Therefore, questions such as what a sustainable water reuse scheme is and how the sustainability of the scheme can be assessed can be answered as this is imperative to the overall success of water reuse schemes and the movement towards contributing to a low carbon, sustainable society. The ISI can be used as a baseline tool by water and wastewater plant operators, water boards and water services providers to evaluate the sustainability of the existing schemes. It can also serve as a guideline for designing and developing water reuse schemes in SA communities where water reuse schemes are to be implemented.

9.2 Conclusions

This section concludes with reference to the objectives of this study which validates the original contribution of this thesis:

1. To critically review integrated water resources reuse concepts, practice, tools, technologies and management. This was achieved through extensive literature survey reported in chapter 2.
2. To estimate water reuse potential in South African water management areas. This was achieved in chapter 3 using linear regression modelling and Bayesian Network modelling approach.

3. From (1), to identify, develop and/or select critical criteria that permeate sustainability attributes and that influence the sustainability of water reuse for potable applications. This was achieved in chapter 5.
4. To develop/adapt a framework for proposed Integrated Sustainability Index for assessing water reuse for domestic potable applications in SA communities. This was achieved in chapter 4.
5. To determine/develop/adapt models that will quantify the impact of criteria on water reuse. This was achieved in chapter 6 and chapter 7.
6. To calibrate and validate the models in (5) using data from literature and selected case studies. This was achieved in chapter 6 and chapter 7.
7. To measure water reuse sustainability performance in selected South African communities using the ISI for different water reuse options. This was achieved in chapter 8.

9.3 Limitations of the ISI

The limitations of the ISI are highlighted below:

i. The values to evaluate each criterion have to be logged in manually for the assessment process.

ii. The hypothesis model to predict intention to accept reuse for potable application , ABEU model and integrated cost analysis model are not incorporated into the DSS software

iii. The treatment train to be assessed is not automatically built by the ISI. Hence, the user must be familiar with treatment train technologies, processes, and their capabilities.

iv. The user is expected to have access to water reuse system operational data for assessment of some technical, environmental and economic criteria

9.4 Future Research

The present study recommends further research in the following areas:

i. Comparing the ISI to other similar indicator initiatives

ii. Testing the hypothesized model with regards to reuse for non-potable applications.
iii. Testing of the linear regression and BN models in other regions across the globe apart from SA and comparing the results.
iv. Addressing the issue of subjectivity in criteria evaluation
v. Incorporating developed criteria evaluation models into the DSS

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